

Coincident Emission of Neutrons and Charged Particles after π^- -absorption in ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{12}\text{C}$, ${}^{59}\text{Co}$ and ${}^{197}\text{Au}$

Inaugural-Dissertation

zur Erlangung der Philosophischen Doktorwürde
vorgelegt der
Philosophischen Fakultät II
der Universität Zürich

von

PETER ADOLF HEUSI
aus Schleithem SH

Begutachtet von Herrn Prof. Dr. R. Engfer

Zürich 1983
Zentralstelle der Studentenschaft



Coincident Emission of Neutrons and Charged Particles after π^- -absorption in ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{12}\text{C}$, ${}^{59}\text{Co}$ and ${}^{197}\text{Au}$

Inaugural-Dissertation

zur Erlangung der Philosophischen Doktorwürde
vorgelegt der
Philosophischen Fakultät II
der Universität Zürich

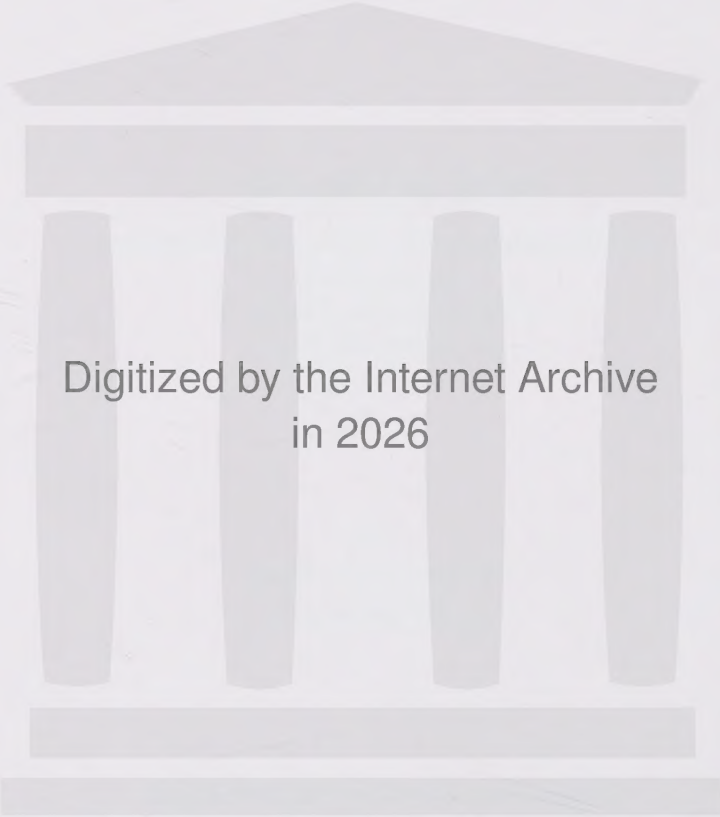
von

PETER ADOLF HEUSI
aus Schleitheim SH

Begutachtet von Herrn Prof. Dr. R. Engfer

Zürich 1983

Zentralstelle der Studentenschaft



Digitized by the Internet Archive
in 2026

https://archive.org/details/IA41507213_0003

Meinen Eltern

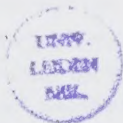
ABSTRACT

Energy spectra $d^3W/dE_1 dE_2 d\cos\theta$ of neutron - charged particle pairs ($n - p$, $n - d$, $n - t$) emitted after the absorption of stopped negative pions in ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{12}\text{C}$, ${}^{59}\text{Co}$ and ${}^{197}\text{Au}$ have been measured for opening angles between 50° and 180° . In the discussion data on the emission of neutron - neutron pairs [Isa82] were included. For the light nuclei ${}^6\text{Li}$ and ${}^7\text{Li}$ and for ${}^{12}\text{C}$ particle pairs emitted without energy loss due to final state interactions, after quasi-free absorption on two, three or four nucleons could be identified by the energy balance. For ${}^{59}\text{Co}$ and ${}^{197}\text{Au}$ the spectra are determined by the final state interactions. Pion absorption on two nucleons (quasi-deuteron mechanism) was found to be the main process. The ratio R of np to pp pairs that absorb the pion was determined for quasi-free absorption on p -shell nucleons of ${}^{12}\text{C}$: $R(p\text{-shell}) = 6.3 \pm 1.4$. For pion absorption in the s -shell of lithium lower limits were found: $R(s\text{-shell}) > 4.4$ for ${}^6\text{Li}$ and $R(s\text{-shell}) > 7.8$ for ${}^7\text{Li}$. These values are larger than the statistical ratios $R_{st} = 2N/(Z-1)$ of np to pp pairs in the nucleus. The shape of the energy spectra of pairs emitted directly after quasi-free absorption on 2 or 4 nucleons could be explained by a simple model for the momentum distribution of the absorbing nucleons. The results are in agreement with the parameters of the momentum distributions known from other reactions. Energy spectra and opening angle distributions were compared with the intranuclear cascade calculations of refs. [Chi81, Hac82]. Lower limits for the probability for pion absorption on heavier clusters (${}^3\text{He}, \alpha$) are $W(hc) > 0.16 / \pi$ -stop for ${}^6\text{Li}$, $W(hc) > 0.11 / \pi$ -stop for ${}^7\text{Li}$ and $W(\alpha) > 0.01 / \pi$ -stop for ${}^{12}\text{C}$.

1. Introduction
2. Basic concepts of stopped pion absorption
 2. 1. Pion absorption on quasi-deuteron and on heavier clusters
 2. 2. Final state interactions
 2. 3. Fermi motion
3. Experimental procedure and data reduction
 3. 1. Mechanical setup
 3. 2. Electronics and data acquisition
 3. 3. Analysis of neutron data
 3. 4. Analysis of charged particle data
 3. 5. Background subtraction and normalization
4. Pion absorption in ${}^6\text{Li}$ and ${}^7\text{Li}$
 4. 1. Absorption on quasi-deuteron
 4. 2. Absorption on heavier clusters
5. Pion absorption in ${}^{12}\text{C}$, ${}^{59}\text{Co}$ and ${}^{197}\text{Au}$
 5. 1. Absorption on quasi-deuteron in ${}^{12}\text{C}$
 5. 2. Absorption on heavier clusters in ${}^{12}\text{C}$
 5. 3. Pion absorption in ${}^{59}\text{Co}$ and ${}^{197}\text{Au}$
6. Summary and conclusion

Appendix A: Simple matrix element for pion absorption

Appendix B: Two-dimensional energy spectra



1. INTRODUCTION

Since the discovery of the pion there has always been a continuous interest in the absorption of pions by nucleons, because this process is one of the primary processes of the strong interaction. Later on this interest was further stimulated by the hope of getting information on the nuclear structure of the absorbing nucleus, particularly on correlations between the nucleons in the nucleus.

Due to energy and momentum conservation a stopped negative pion is absorbed by at least two correlated nucleons; the momenta of the individual nucleons in the nucleus are too small to allow the absorption on a single nucleon. The rest mass energy of the pion is transferred to the absorbing nucleons, which then may leave the nucleus directly (primary nucleons), or undergo final state interactions with the residual nucleus and leave the nucleus with reduced energy (secondary nucleons). The spectrum of the secondary nucleons is mainly determined by these final state interactions, and the information on the absorption process itself is hidden. The remaining nucleus may be excited and de-excites by the emission of γ -rays or particle evaporation.

The present work gives the results of recent experiments investigating coincident neutron - charged particle emission after stopped negative pion absorption in ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{12}\text{C}$, ${}^{59}\text{Co}$ and ${}^{197}\text{Au}$. These data supplement previous work on stopped pion absorption published in refs. [Har78, Pru79, Pru81, Sen81, Isa82, Sen82, Isa83] on the emission of neutrons and charged particles and on neutron - neutron and charged particle - charged particle pairs. The interpretation of the present data includes also the new data on coincident neutron - neutron emission by Isaak et al. [Isa82]. First results have been published [Heu82].

Previous measurements on coincident neutron - proton emission have been done by Ozaki et al. [Oza60], for several targets, with lower statistics and at two opening angles only. Nordberg et al. [Nor68] measured neutron - neutron and neutron - proton coincidences for different targets from lithium to lead at different angles. The work of Lee et al. [Lee72] investigated the coincident emission of neutrons and charged particles ($n - p$, $n - d$ and $n - t$) emitted after pion absorption in ^{12}C .

In chapter 2 the basic concepts on stopped pion absorption are exposed. Chapter 3 presents the experimental technique and gives information on the analysis of the data. In chapters 4 and 5 the experimental results are presented and discussed for ^6Li , ^7Li and for ^{12}C , ^{59}Co and ^{197}Au . Chapter 6 gives a summary and the conclusions.

2. BASIC CONCEPTS OF PION ABSORPTION IN NUCLEI

2. 1. PION ABSORPTION ON QUASI-DEUTERONS AND ON HEAVIER CLUSTERS

In the present literature two basic concepts for the primary absorption process are discussed, namely absorption on a nucleon pair (quasi-deuteron) and absorption on heavier clusters. Most recent models of the stopped pion absorption process in nuclei consider the absorption on a pair of nucleons. In this mechanism the final state consists of a nucleon pair (either $n - n$ or $n - p$) where each nucleon has a kinetic energy of about $1/2$ of the pion rest mass and their total momentum is zero. One expects therefore a back to back emission of $n - n$ or $n - p$ pairs. The initial Fermi motion of the absorbing nucleons is responsible for a broadening of the opening angle distribution and the nucleon energy spectra. Final state interactions (discussed in sect. 2.2.) give rise to further distortions of the measured spectra.

An important parameter describing the absorption process is the ratio R of np to pp pairs that can absorb the pion:

$$R = \frac{\Gamma(\pi^- A \longrightarrow A-2 + n + n)}{\Gamma(\pi^- A \longrightarrow A-2 + n + p)}$$

This ratio is related to the fundamental absorption width by

$$R = \frac{2N}{Z-1} \frac{\Gamma(\pi^- np \longrightarrow n + n)}{\Gamma(\pi^- pp \longrightarrow n + p)}$$

where $2N/(Z-1)$ is the statistical ratio of np to pp pairs in a nucleus with Z protons and N neutrons. The values for R are still not determined unambiguously. Experimental values for R in ^{12}C have been determined in previous coincidence experiments. Ozaki et al. [Oza60] obtained $R = 5.0 \pm 1.5$, whereas Nordberg et al. [Nor68] got a value of $R = 2.5 \pm 1.0$ and Lee et al.

[Lee72]* obtained $R = 8.8 \pm 1.3$. Pruys et al. [Pru81] found by comparing the single proton and neutron yields a lower limit of $R \geq 2.4$. On the theoretical side, the situation is by no means less puzzling. In a microscopic calculation Shimizu and Faessler [Shi80] obtained $R = 8.5$ for absorption in the p-shell of ^{12}C if they included π and ρ -exchange and $R = 15$ if $\pi\pi$ -exchange was added. In the microscopic calculation of ref. [K&182] a value $R = 1.25$ was obtained for pion absorption in ^{16}O . Values for R were obtained by Chiang and Hüfner [Chi81] by fitting the experimental spectra of the emitted particles in a pre-equilibrium calculation, using R as a free parameter. For ^{12}C a value of $R = 13 \pm 6$ was obtained. For heavy nuclei, high values for R were obtained by the measurement and calculation of Orth et al. [Ort82].

In principle the pion can be absorbed not only by two but also by three, four or more nucleons. This process is called cluster absorption and is less important than the quasi-deuteron mechanism. A clear indication for absorption on α or ^3He -clusters has been found from the energy spectra of deuterons and tritons emitted from ^6Li and ^7Li [Sen82]. In the same work evidence for pion absorption on ^4Li -clusters was found by investigating charged particle - charged particle coincidences emitted from ^6Li and ^7Li . Lee et al. [Lee72] concluded from their high neutron - triton coincidence yield a lower limit of $0.046 / \pi$ -stop for ^{12}C . In the calculated spectra of tritons emitted after pion absorption in medium and heavy nuclei, Hachenberg [Hac82] explained part of the measured yields to be due to final state interactions of the primary nucleon pair with the residual nucleus. The rest was explained by a non-zero probability of pion absorption on heavier clusters. An upper limit of $0.25 / \pi$ -stop was given. A recent calculation [Ber78] of

* In ref. [Lee72] the n - n data of ref. [Che69] were used to determine R .

pion absorption rates in ^{12}C showed that at most 10 - 20 % of the measured absorption rate have to be explained by mechanisms involving more than two nucleons.

The absorption on an α -cluster is thought to be one of the most important processes involving more than two nucleons [But80]. In this case the following reactions are possible. The numbers give the relative probabilities of the processes for pion absorption in ^4He :

- (i) $\pi^- + ^4\text{He} \longrightarrow n + t \quad 19.4 \pm 1.8 \quad \%/ \pi\text{-stop [Blo63]}$
- (ii) $\pi^- + ^4\text{He} \longrightarrow n + n + d \quad 58 \pm 7 \quad \%/ \pi\text{-stop [Cal70]}$
- (iii) $\pi^- + ^4\text{He} \longrightarrow n + n + n + p \quad 26 \pm 6 \quad \%/ \pi\text{-stop [Cal70]}.$

In order to establish the absorption on an α -cluster (i.e. absorption on four nucleons) in a coincidence experiment, reaction (i) gives the most conclusive results. After quasi-free absorption, the emitted triton carries 1/4 and the neutron 3/4 of the available energy (kinematics of quasi-free decay). A peak at such a high neutron energy cannot be produced by final state interactions and hence this reaction allows us to give lower limits on the amount of pion absorption on α -clusters.

Reactions (ii) and (iii) are mainly due to absorption on two nucleons in the ^4He nucleus, with the residual nucleons acting as spectator [Zio70, Cer81]. Thus also in ^4He only part of the pions are absorbed by four nucleons.

2. 2. FINAL STATE INTERACTIONS

The yields of the emitted particles and their energy spectra are strongly influenced by the final state interactions of the primary particles with the residual nucleus. Such interactions are e.g. internal scattering, knockout and pick-up reactions. For heavy nuclei these processes are dominant in the experimental results. In the intranuclear cascade calculation of Chiang and Hüfner [Chi81] the probability that both primary nucleons leave the nucleus without final state interaction is 33 % for ^{12}C and 18 % for ^{197}Au . There are two ways to obtain

information on the primary absorption process from the experimental data. The first method requires a model for the pion absorption process, which takes the final state interactions fully into account. The pre-equilibrium models of refs. [Gad76, Ilj76, But80, Hac80, Chi81, Hac82, Dat82, Cha82] have been used to calculate single particle spectra for medium and heavy nuclei. The basic information on the absorption process served as an input for the calculation and could be varied to fit the experimental spectra. Since the pre-equilibrium processes are very complicated, the results do not seem to be strongly dependant on the input. A more sensitive method to look for the primary process in light nuclei is the study of processes where two primary particles are emitted leaving the residual nucleus undisturbed. These processes can be selected experimentally by looking for events where the sum of the energies of the emitted particles (including the recoil energy of the residual nucleus) is equal to the Q-value of the primary absorption and emission process. Under the assumption that proton - nucleus and neutron - nucleus final state interactions are the same, conclusions from these selected data may be generalized to all two nucleon absorption processes.

2. 3. FERMI MOTION

Without Fermi motion and final state interactions pion absorption on a quasi-deuteron would lead to the emission of two 60 MeV nucleons (half of the pion mass minus the binding energies of the nucleons), back to back, and a residual nucleus at rest. Due to their Fermi motion the emitted nucleons have an energy distribution with a mean energy of about 60 MeV and the residual nucleus has a recoil energy which is determined by the sum of the momenta of the absorbing nucleons before the absorption. Thus, in this quasi-free absorption model, the shapes of the energy spectra and the opening angle distribution of the emitted nucleons depend only on the Fermi motion of the

absorbing nucleons. If the absorption is assumed to occur at zero range for the two nucleons, the transition matrix element depends only on the sum of the momenta of the absorbing nucleons (the momentum of the quasi-deuteron) [Sak66,Sak75]. The momentum distribution of the quasi-deuterons has been measured in the (p,pd) reaction [Kit75, Alb80]. The momentum distribution and thus the matrix element could be fitted with a Gaussian [Kit75]:

$$|M|^2 \sim e^{-\left(\frac{P}{\gamma}\right)^2} \quad (1)$$

P is the momentum of the quasi-deuteron (and of the recoiling nucleus) and γ is a fit parameter. A theoretical justification for this Gaussian matrix element is given in appendix A. In the harmonic oscillator shell model, the parameter γ depends on the harmonic oscillator parameter $\beta = \sqrt{\hbar/m\omega}$ [Appendix A, Sak66]:

$$\gamma = \sqrt{\frac{n(A-n)}{A}} \frac{\hbar}{\beta}$$

A is the atomic number of the absorbing nucleus and n is the number of nucleons on which the pion is absorbed. Nordberg et al. [Nor68] used the same Gaussian matrix element to interpret their measurements. In fig. 2.3.1. this matrix element is compared with the more sophisticated matrix element of Koltun and Reitan [Kol67]. The shapes differ only at the very high momenta and the experiments are not sensitive to this difference.

Using the Gaussian matrix element (eq. 1) for pion absorption on a quasi-deuteron or on an α -cluster one can calculate the shapes of the energy spectra and the opening angle distribution of the emitted particles. The differential distribution is given by first order perturbation theory.

$$d^3W = 2\pi |M|^2 d^3R \quad (2)$$

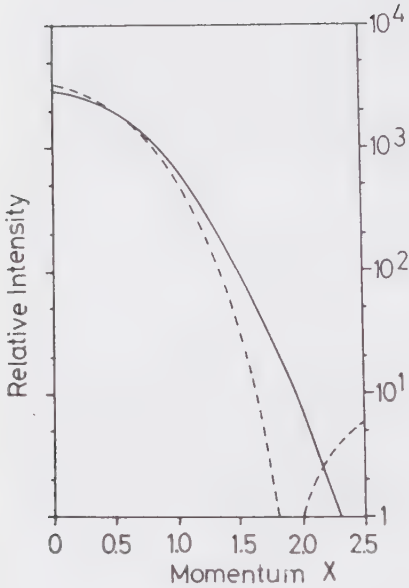


Fig. 2.3.1. The intensities $\sim |M|^2$ for pion absorption in ${}^6\text{Li}$ as a function of the recoil momentum.

$X = P\beta/\sqrt{2} \hbar = P/(170 \text{ MeV}/c)$.

$|M|^2 \sim \exp(-3X^2/2)$ (solid line) and $|M|^2$ from ref. [Kol67] (dashed line).

The phase space factor d^3R is given by

$$d^3R \sim \delta^3(\vec{P} + \vec{p}_1 + \vec{p}_2) \delta(E_i - E_f) d^3\vec{P} d^3\vec{p}_1 d^3\vec{p}_2 \quad (3)$$

where $\vec{p}_1$ and $\vec{p}_2$ are the momenta of the emitted particles (two nucleons or a neutron - triton pair) and $\vec{P}$ is the recoil momentum of the residual nucleus. The difference of initial and final energies is $E_i - E_f = Q - (E_1 + E_2 + E_R)$. Q is the mass difference of initial and final state, $Q = m_\pi + m_A - m_{A-n} - m_1 - m_2$ with $n = 2$ for pion absorption on a quasi-deuteron, and $n = 4$ for pion absorption on an α -cluster. E_1 , E_2 , E_R and m_1 , m_2 , m_A , m_{A-n} are the kinetic energies and masses of the two emitted particles and the nuclei involved. Integrating eq. 2 over the unobserved variables gives

$$\frac{d^3W}{dE_1 dE_2 d\cos\theta} \sim \delta(E_i - E_f) \sqrt{E_1 E_2} e^{-\frac{2}{\gamma^2} (m_1 E_1 + m_2 E_2 + 2\sqrt{m_1 E_1 m_2 E_2} \cos\theta)} \quad (4)$$

θ is the opening angle of the two emitted particles.

An analytical expression for the energy spectrum of one of the emitted particles can be obtained from eq. 4 if one neglects the small recoil energy. For instance the energy spectrum of tritons in coincidence with neutrons emitted at 180° after pion absorption on α -clusters is

$$\left(\frac{dW}{dE_t}\right)_{\theta=180^\circ} \sim \sqrt{E_t(Q-E_t)} e^{-\frac{4m}{\gamma^2} (E_t - \sqrt{3E_t(Q-E_t)})} \quad (5)$$

Similar expressions for the energy spectrum of neutrons emitted after pion absorption on a quasi-deuteron are given in refs. [Muk79] and [Chi81] and for tritons emitted after pion absorption on an α -cluster in ref. [Hac82]. For a comparison with the experimental data eq. 2 was integrated numerically (using the CERN program FOWL [Jam70]) including the experimental energy thresholds and energy resolution (see sect. 4. and 5.).

3. EXPERIMENTAL PROCEDURE AND DATA REDUCTION

3. 1. MECHANICAL SETUP

The experiment was carried out at the $\pi E3$ beam of the Swiss Institute for Nuclear Research (SIN). The experimental setup is shown in fig. 3.1.1. The negative pions with an initial momentum of 82 MeV/c were moderated in a polyethylene degrader and were stopped in the target which was mounted in the centre of a vacuum chamber. The incoming pion was detected by a

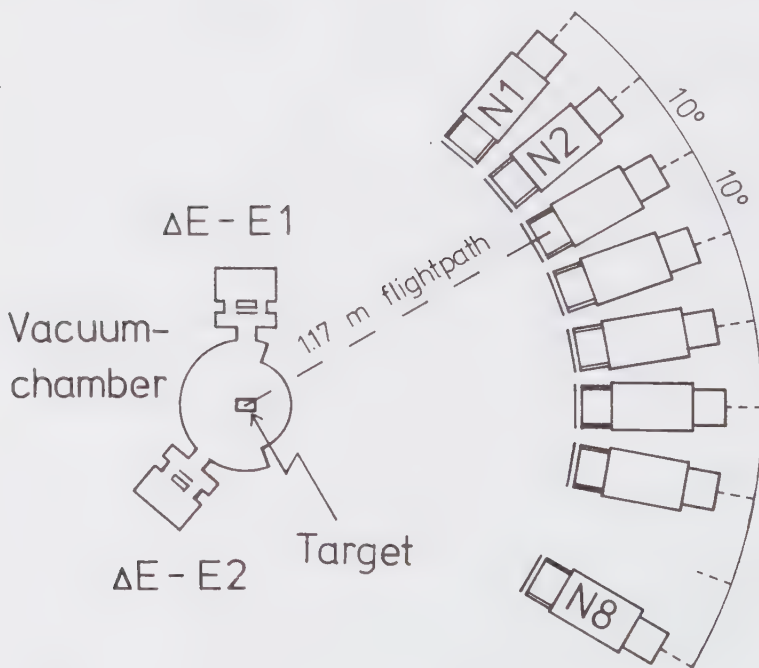


Fig. 3.1.1. Experimental set-up for neutron - charged particle coincidence measurement. View is parallel to the vertical beam axis.

conventional beam telescope of three plastic scintillator counters before the target (1,2,3) and one after the target (4). The logical signature for a pion that stopped was therefore $123\bar{4}$. The targets had a size of 4 cm x 6 cm and were mounted at an angle of 22.5° between target plane and beam-axis. The thickness of the targets and typical rates of stopped pions ($123\bar{4}$) were:

${}^6\text{Li}$	83 mg/cm ²	$1.4 \cdot 10^5$ /s
${}^7\text{Li}$	107 mg/cm ²	$1.8 \cdot 10^5$ /s
${}^{12}\text{C}$	110 mg/cm ²	$3.9 \cdot 10^5$ /s
${}^{59}\text{Co}$	158 mg/cm ²	$2.3 \cdot 10^5$ /s
${}^{197}\text{Au}$	243 mg/cm ²	$2.2 \cdot 10^5$ /s.

The emitted charged particles were observed by two $\Delta E - E$ detector systems consisting of a 0.5 mm thick silicon surface barrier detector of 43 mm diameter and a 15 mm thick intrinsic germanium detector. The solid angle of these detector systems of 12.1 msr was limited by a collimator placed in front of the Si detector at 306 mm from the target (diameter = 38 mm). To prevent the detection of charged particles not coming out of the target (e.g. particles stemming from pion stops in the beam telescope counter 3), a further collimator with 30 mm diameter was placed at 74 mm from the target.

The neutrons left the vacuum chamber through a thin (1mm) steel window and were detected by eight NE213 liquid scintillator detectors which were placed at a distance of 117 cm from the centre of the target. The scintillators were 4" thick and had a diameter of 5". They were coupled to Philips XP2041 phototubes. The energy of the neutrons was determined by their time-of-flight. In front of the neutron detectors a thin plastic scintillator was placed to veto signals produced by charged particles. The solid angle of the neutron detectors was 9.2 msr.

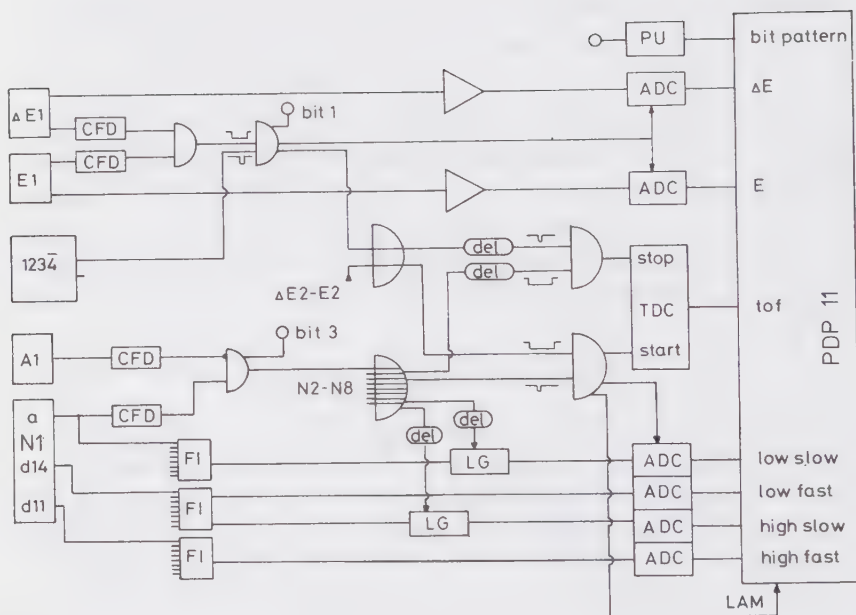


Fig. 3.2.1. Detector read-out system. $\Delta E1$ and $E1$ are the Si and Ge detectors of the charged particle telescope 1. (The identical scheme for the telescope 2 is not shown.) 1234 is the pion stop signal. N1 is the neutron counter 1 with A1 as veto counter for charged particles. The anode signal of the photomultiplier (a) is used to give the start signal of the time-of-flight measurement, the stop signal is timed by the incoming pion (1234). The pulse height of the anode (a) and dynodes 14 and 11 (d14, d11) signals are used for the n- γ -discrimination in the off-line analysis. The signals of the eight neutron detectors are added in fan-in units. For every detector that fired a bit is set in the parameter unit PU. The resulting bit pattern allows the identification of the detector combination (opening angle). ADC and TDC are the analog to digital converter and time to digital converter, respectively; CFD is a constant fraction discriminator and LG is a linear gate. The LAM signal is the trigger which initializes the readout of the CAMAC units by the PDP 11 computer.

3. 2. ELECTRONICS AND DATA ACQUISITION

Fig. 3.2.1. shows the scheme of the electronics used in the experiment. The analog signals of the neutron and charged particle detectors were digitized in ADC's, read via CAMAC by the PDP 11 computer and then stored on magnetic tape. The trigger of the data acquisition system (IAM) required a pion stop in the target, in coincidence with a charged particle detected in one of the charged particle telescopes and in coincidence with an uncharged particle in one of the neutron detectors. The pion stop signal was vetoed if either the computer or the electronics was busy, or if more than one pion stop was registered within a time interval of 200 ns (pile-up). The start and stop signal of the time measurement were determined by the time of the neutron signal and the time of the incoming pion in the pion telescope counter 2, respectively. To get the three-dimensional distribution $d^3W/dE_n dE_c d\cos\theta$ eight 16-bit words containing the following information were stored on magnetic tape:

word 1	: identification of detector (angle)
word 2	: ΔE , energy loss of charged particle in Si detectors
word 3	: E, energy of charged particle deposited in Ge detector
word 4 - 7	: pulse height information of neutron detectors (see sect. 3.3.)
word 8	: neutron time-of-flight

3. 3. ANALYSIS OF NEUTRON DATA

Neutrons and gammas were separated off-line by pulse-shape discrimination using the analog signals of the neutron detectors. In order to increase the dynamic range in which discrimination was possible, two ranges were used. For each range the signal was separated into a 'fast' and a 'slow'

component. The slow component of a signal produced by an electron is higher than that of a proton with the same pulse height of the fast component. Therefore a discrimination between neutrons (proton signal) and gammas (electron signal) was possible using the following expression:

$$dn = a \frac{'fast'}{'slow' + b} - \frac{'fast'}{c} - d$$

The parameters a , b , c and d were adjusted for optimal discrimination (see fig. 3.3.1.). In the off-line analysis a threshold equivalent to 3 MeV neutron energy was set on the pulse height of the dynode 14 signal. The energy calibration of the pulse height was done using gammas from the radioactive sources ^{22}Na , ^{137}Cs and ^{88}Y .

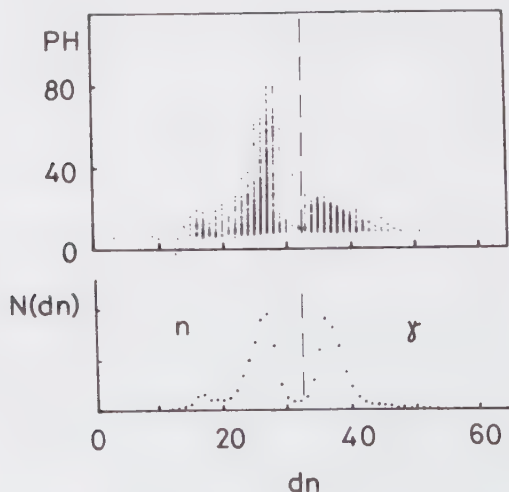


Fig. 3.3.1. Two-dimensional distribution of neutral events $N(\text{PH}, dn)$ ('high' dynamic range) as a function of the pulse height PH and the discrimination function dn (dn is defined in the text) and projection $N(dn)$. Events on the left of the dashed line are identified as neutrons, those on the right as γ 's.

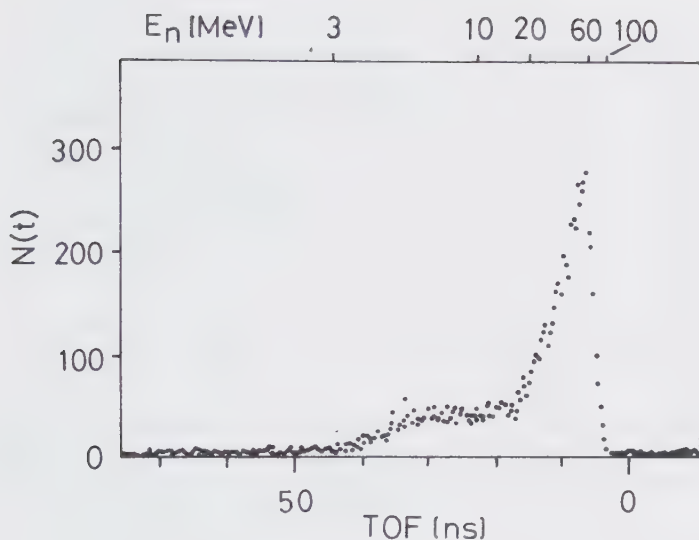


Fig. 3.3.2. Time-of-flight spectrum $N(t)$ of neutrons emitted in coincidence with a charged particle at an opening angle of 180° . A threshold equivalent to 3 MeV neutron energy was set on the pulse height of the neutron signal.

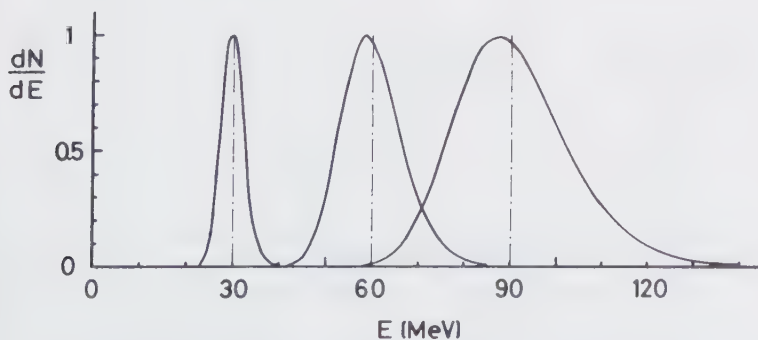


Fig. 3.3.3. Energy resolution functions for neutron energies of 30, 60 and 90 MeV calculated for a time resolution of 1.3 ns FWHM.

Fig. 3.3.2. shows the time-of-flight spectrum of neutrons emitted in coincidence with a charged particle at an opening angle of 180° after pion absorption in ^{12}C . The time-of-flight was corrected for walk of the constant fraction discriminator and was then converted to energy. The time resolution was 1.3 ns FWHM. In fig. 3.3.3. the energy resolution functions for neutrons with 30, 60 and 90 MeV are shown. They are calculated by a Monte-Carlo method assuming a Gaussian time distribution with 1.3 ns FWHM.

The efficiency curve for a 5" diameter, 4" thick NE213 liquid scintillator is shown in fig. 3.3.4. for a detection threshold of 3 MeV neutron energy. It was calculated using a Monte-Carlo code which is based on the code by Del Guerra et al. [Gue76] and was updated by Vernin [Ver78]. To check the reliability of the results given by this code, efficiency curves for several different detector geometries were calculated and compared with the measured efficiencies of refs. [Dro72, Fow80, Rid74, Nau74].

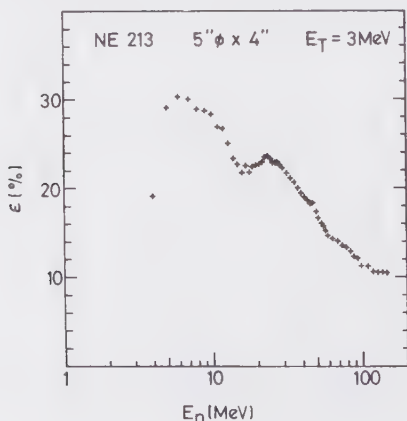


Fig. 3.3.4. Calculated neutron detection efficiency ϵ for a 5" diameter and 4" thick neutron detector of type NE213 for a neutron energy threshold of $E_T = 3$ MeV (equivalent to an electron energy $E_e = 973$ keV).

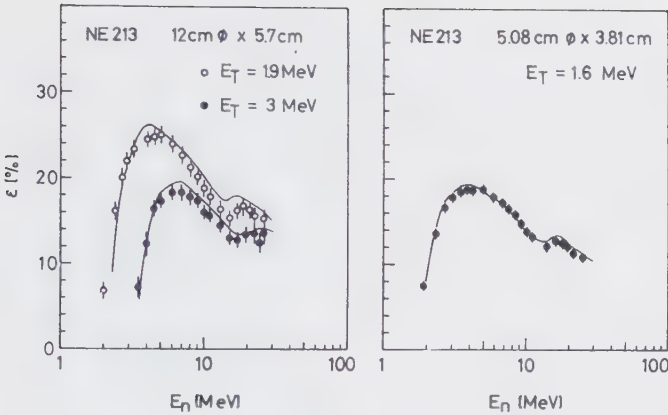


Fig. 3.3.5. Comparison of our efficiency calculations (solid lines) with measurements for NE213 (ref. [Dro72]: 12 cm ϕ x 5.7 cm and neutron energy threshold $E_T = 1.9$ and 3 MeV; ref. [Fow80]: 5.08 cm ϕ x 3.81 cm and $E_T = 1.6$ MeV).

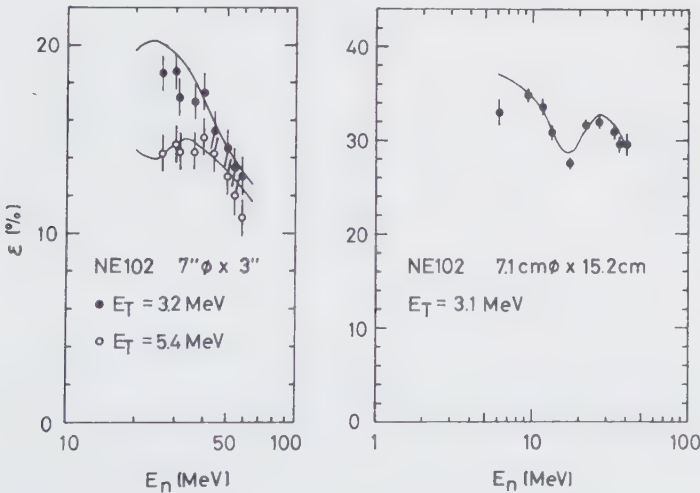


Fig. 3.3.6. Comparison of our efficiency calculations (solid lines) with measurements for NE102 (ref. [Rid74]: 7" ϕ x 3" and $E_T = 3.2$ and 5.4 MeV; ref. [Nau74]: 7.1 cm ϕ x 15.2 cm and $E_T = 3.1$ MeV).

In fig. 3.3.5. our results are compared with the measurement of Drosig et al. [Dro72] for a 12 cm $\emptyset$ x 5.7 cm NE213 detector, and with the measurements of Fowler et al. [Fow80] for a small 5.08 cm $\emptyset$ x 3.81 cm NE213 detector. For energies above 30 MeV the comparison (see fig. 3.3.6.) is done for the 7" $\emptyset$ x 3" detector of Riddle et al. [Rid74]* and for the 7.1 cm $\emptyset$ x 15.2 cm NE102 detector of Mc Naughton et al. [Nau74]. If we assume a 10 % accuracy for our calculation, the agreement is reasonable.

3. 4. ANALYSIS OF CHARGED PARTICLE DATA

For the measurements of the charged particle energy, the energy loss in the thin Si detector and the energy deposited in the thick Ge detector was recorded. For the calibration of these detectors the same methods were used as in ref. [Sen82]. The Si detector was calibrated with an α -source (^{241}Am , $E_{\alpha} = 5.4$ MeV), whereas the Ge detector was calibrated with the photopeaks of a ^{60}Co source ($E_{\gamma} = 1.17$ MeV, 1.33 MeV). Linearity checks were applied using a signal generator. Small corrections to the calibration were determined using the known relation between ΔE and E for protons, deuterons and tritons. The reaction channel $^6\text{Li}(\pi^-, \text{tt})$, producing two monoenergetic tritons of 61.63 MeV was used as the most accurate direct calibration. This method was applied in the lithium measurements.

In the off-line analysis the charged particles (p,d,t) were identified using the following discrimination function:

* With reference to Anghinolfi et al. [Ang79] the data points of the 3.2 MeV curve were shifted by 2%, assuming an error in the lettering of fig. 3 of ref. [Rid74].

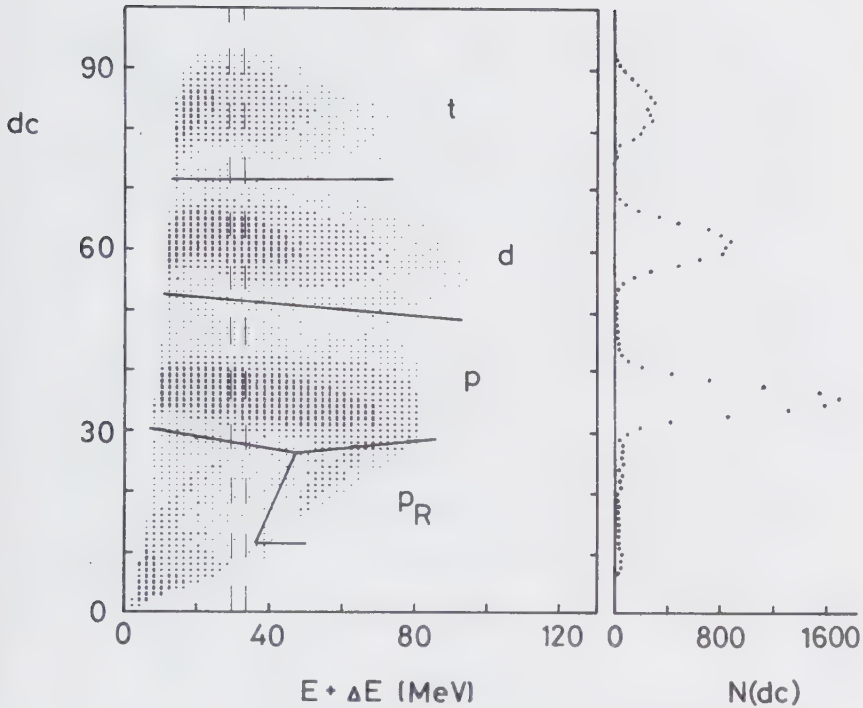


Fig. 3.4.1. Two-dimensional distribution $N(dc, \Delta E + E)$ of charged particles as a function of the discrimination function and of the sum of the energies deposited in the charged particle detectors. (dc is defined in the text). Events in the regions p , d , t were identified as protons, deuterons and tritons. The region p_R contains high-energy protons, that did not stop in the Ge detector and therefore had to be evaluated in $\Delta E_1 - \Delta E_2$ technique. The picture on the right shows the projection $N(dc)$ for $30 < \Delta E + E < 34$ MeV (dashed lines).

$$dc = (E + \Delta E)^b - E^b \quad b = 1.73$$

Fig. 3.4.1. shows a scatterplot of the intensity of charged particles as a function of dc and $E + \Delta E$. Charged particles falling in the regions p, d, t were identified as protons, deuterons and tritons, respectively. Charged particles in the area labelled p_R are high energy protons that did not stop in the Ge detector ($E_p > 78$ MeV) and hence their energies had to be determined in $\Delta E_1 - \Delta E_2$ technique.

The energy of the emitted charged particle was determined using a first order correction for the energy loss in the target. It was assumed that all charged particles were emitted in the centre of the target. E_0 being the measured energy of the charged particle and $\Delta E(E)$ the energy loss in the target, calculated using the Bethe-Bloch formula, the initial energy of the emitted particle was approximated by

$$E = E_0 + \Delta E(E_0 + \Delta E(E_0)).$$

Single charged particle spectra are in agreement with previous results [Sen82, Pru81]*.

3. 5. BACKGROUND SUBTRACTION AND NORMALIZATION

The only background which was found to be important came from events where charged particles, emitted after pion absorption in the target were in random coincidence with neutrons. Such events showed a flat time distribution. The spectrum of the

* The yields of the charged particles for ${}^6\text{Li}$ in ref. [Sen82] had to be increased by 18% due to an improved normalization.

accompanying charged particle was the same as that of the singles measurements. The amount of this background was determined from the time-of-flight spectrum for negative times. It was found to be less than 4 % for n - p coincidences at 180° (threshold 20MeV), and about 15 % for n - p coincidences at 140° . Background not related to the target was determined in short runs with the target removed. It was found to be less than 1 % and was neglected. The low background of this type was due to the collimator system in front of the charged particle detectors which prevented the charged particles produced by pions that stopped in the beam counter 3 from reaching the detectors.

For the absolute normalization of the neutron - charged particle data a reference measurement of single charged particle spectra was done. The yields of this measurement were compared to those measured in previous work [Sen82,Pru81].

If $\frac{d^2W(\theta)}{d\Omega_n d\Omega_c}$ is the yield of neutron - charged particle coincidences [number of pairs/(sr² π -stop)], then the number of pairs $N(\theta)$, measured with the two detector systems with solid angles $\Delta\Omega_n$ and $\Delta\Omega_c$ at an opening angle θ is given by

$$N(\theta) = \frac{d^2W(\theta)}{d\Omega_n d\Omega_c} \Delta\Omega_n \Delta\Omega_c N_\pi$$

where N_π is the number of stopped pions. N_π is proportional to the number b of pions in the beam, $N_\pi = f b$.

After integration,

$$\frac{dW(\theta)}{d\cos\theta} = 8\pi^2 \frac{N(\theta)}{\Delta\Omega_n \Delta\Omega_c f b}$$

The constant f and the effective solid angle $\Delta\Omega_c$ of the charged particle telescope had to be determined from the measurement of single charged particles.

For the single charged particle measurement, the number of particles detected is

$$N_s = \frac{dW}{d\Omega_c} \Delta\Omega_c f b_s = \frac{W}{4\pi} \Delta\Omega_c f b_s$$

where W is the yield of charged particles emitted per pion stop. The yield W has been previously determined [Sen82, Pru81]

By measuring N_s and b_s , the unknown product $\Delta\Omega_c f = 4\pi N_s / (W b_s)$ could be determined.

Thus

$$\frac{dW(\theta)}{d\cos\theta} = \frac{8\pi^2 N(\theta)}{\Delta\Omega_n} \frac{b_s}{b} \frac{W}{4\pi N_s}$$

and

$$\frac{d^3W(\theta, E_1, E_2)}{d\cos\theta dE_1 dE_2} = 2\pi \frac{\frac{d^2N(\theta, E_1, E_2)}{dE_1 dE_2}}{\Delta\Omega_n} \frac{b_s}{b} W$$

In order to allow an integration of the opening angle distribution, the data were fitted using the empirical formula

$$\frac{dW(\theta)}{d\cos\theta} = A \exp\left(\frac{\theta - 180^\circ}{B}\right)^2 + C \exp(D\theta) + E$$

In the figures which show the opening angle distributions, the result of the fits is given. The total number of detected particle pairs is then obtained by

$$W = \int \frac{dW(\theta)}{d\cos\theta} \sin\theta d\theta$$

4. PION ABSORPTION IN ${}^6\text{Li}$ AND ${}^7\text{Li}$

The study of stopped negative pion absorption in the light nuclei ${}^6\text{Li}$ and ${}^7\text{Li}$ is especially interesting, because one can hope that the spectra of the emitted particles are mostly determined by the primary absorption process, and that final state interactions between the primary nucleons and the residual nucleus play only a minor role. Two-dimensional neutron - neutron [Isa82] and neutron - charged particle ($n - p$, $n - d$, $n - t$) energy spectra and opening angle distributions were measured for an angular range of $50^\circ < \theta < 180^\circ$ and $75^\circ < \theta < 180^\circ$, respectively. Sect. 4.1. presents the data on the emission of neutron - neutron and neutron - proton coincidences and deals with the quasi-deuteron absorption mechanism. Sect. 4.2. is devoted to the presentation of the data on neutron - deuteron and neutron - triton emission which are explained by pion absorption on heavier clusters.

4. 1. ABSORPTION ON QUASI-DEUTERONS

In figs. 4.1.1. and 4.1.2. the two-dimensional energy spectra of coincident neutron - neutron and neutron - proton pairs emitted after pion absorption in ${}^6\text{Li}$ and ${}^7\text{Li}$ are shown for an opening angle θ of 180° *. The neutron - neutron spectra both show two characteristic enhancements. After the quasi-free absorption of the pion on a neutron - proton pair in the p-shell of the nucleus (p-shell absorption), two neutrons with energies $E_n = Q/2$ [$Q({}^6\text{Li}(\pi^-, nn){}^4\text{He}) = 135 \text{ MeV}$; $Q({}^7\text{Li}(\pi^-, nn){}^4\text{He}+n) = 128 \text{ MeV}$] are emitted back to back. Due to the Fermi motion of the absorbing pair, the energy spectrum is broadened in the

* The measurement with two detectors geometrically at 180° will be referred to as the 180° measurement, although the mean opening angle θ for this geometry is 177.5° for $n - n$ and 175° for $n - c$.

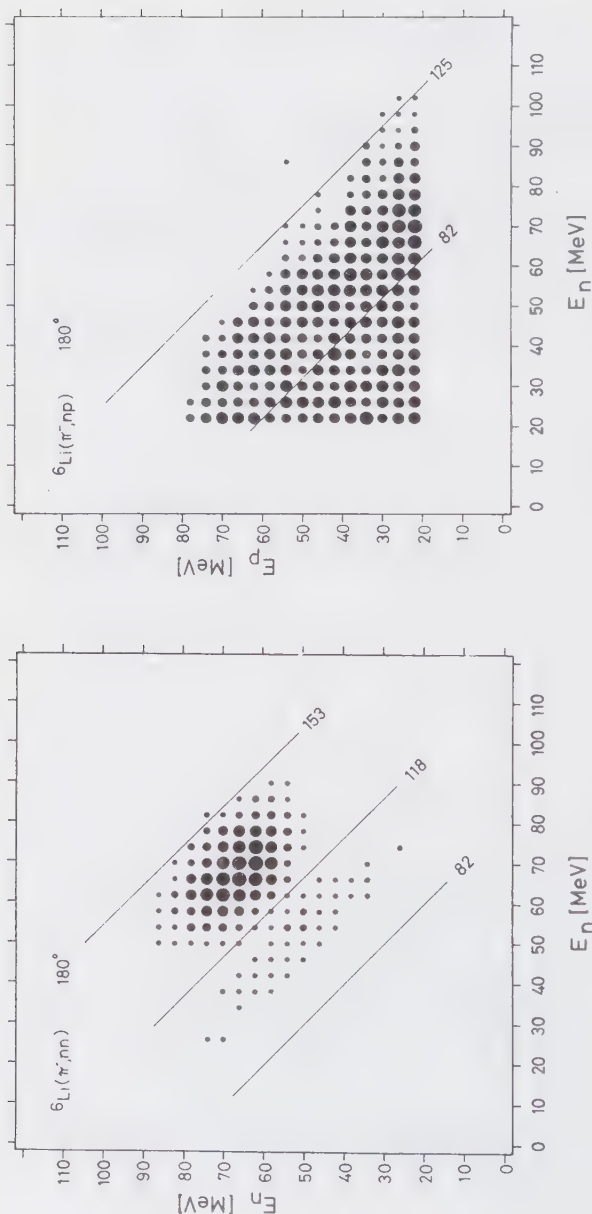


Fig. 4.1.1. Two-dimensional energy spectra $d^3W/dE_1dE_2dcos\theta$ ($\theta = 180^\circ$) of neutron - neutron and neutron - proton pairs emitted after pion absorption in ${}^6\text{Li}$ ($E_n, E_p > 20$ MeV). The area of the points is proportional to the intensity. The spectra are normalized individually to the maximum of the two-dimensional distribution. Points for intensities below 10% of the maximum are not plotted. The maximum of the $n - p$ distribution is by a factor of 36 lower than that of the $n - n$ distribution. Events from p-shell absorption were defined by the condition $118 < E_S < 153$ MeV and events from s-shell absorption were defined by $82 < E_S < 118$ MeV (< 125 MeV for $n - p$). E_S is the recoil-corrected sum energy: $E_S = E_{n1} + E_{n2}$ (or E_p) + E_R . In appendix B the spectra are also given numerically.

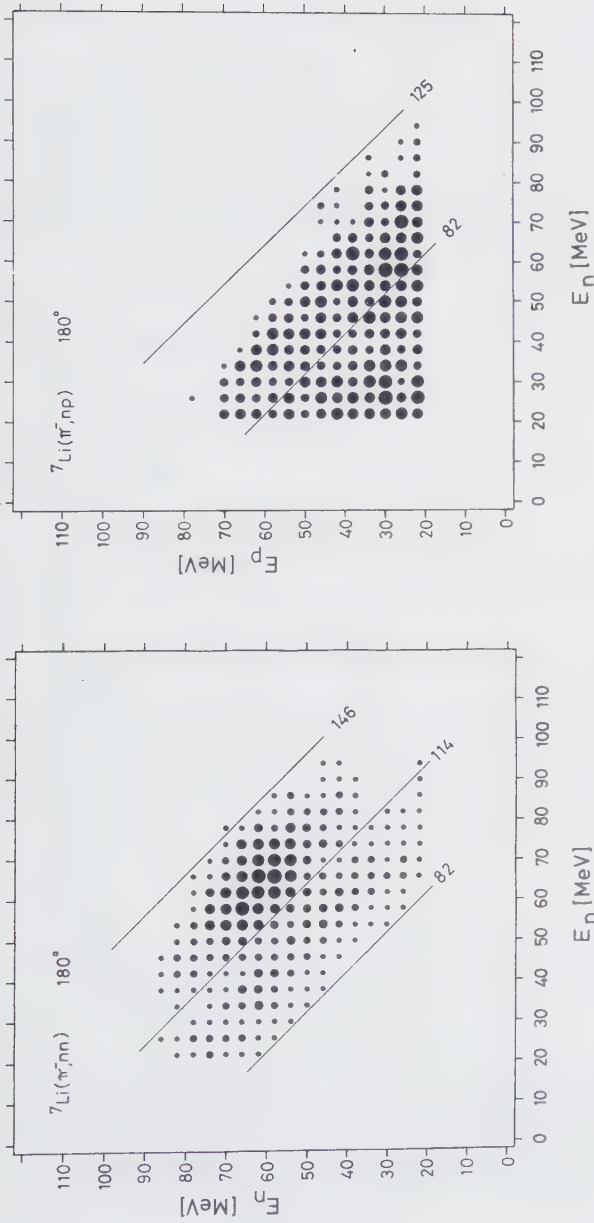


Fig. 4.1.2. Two-dimensional energy spectra $d^3W/dE_1 dE_2 d\cos\theta$ ($\theta = 180^\circ$) of neutron - neutron and neutron - proton pairs emitted after pion absorption in ${}^7\text{Li}$ ($E_n, E_p > 20$ MeV). The maximum of the $n - p$ distribution is by a factor of 18 lower than that of the $n - n$ distribution. Events from p-shell absorption were defined by the condition $114 < E_s < 146$ MeV and events from s-shell absorption were defined by $82 < E_s < 114$ MeV (< 125 MeV for $n - p$). In appendix B the spectra are also given numerically. (See also fig. 4.1.1.).

direction of constant $E_{n1} + E_{n2}$. This process therefore is responsible for the peaks around $E_{n1} = E_{n2} = 65$ MeV. The second enhancement (around 50 - 55 MeV) is produced by $n - n$ events emitted after the quasi-free absorption of the pion on at least one s-shell nucleon. In what follows this process is referred to as s-shell absorption. The total energy available in this process is lower by at least 20 MeV. The energy spectrum and the opening angle distribution (fig. 4.1.4.) of the

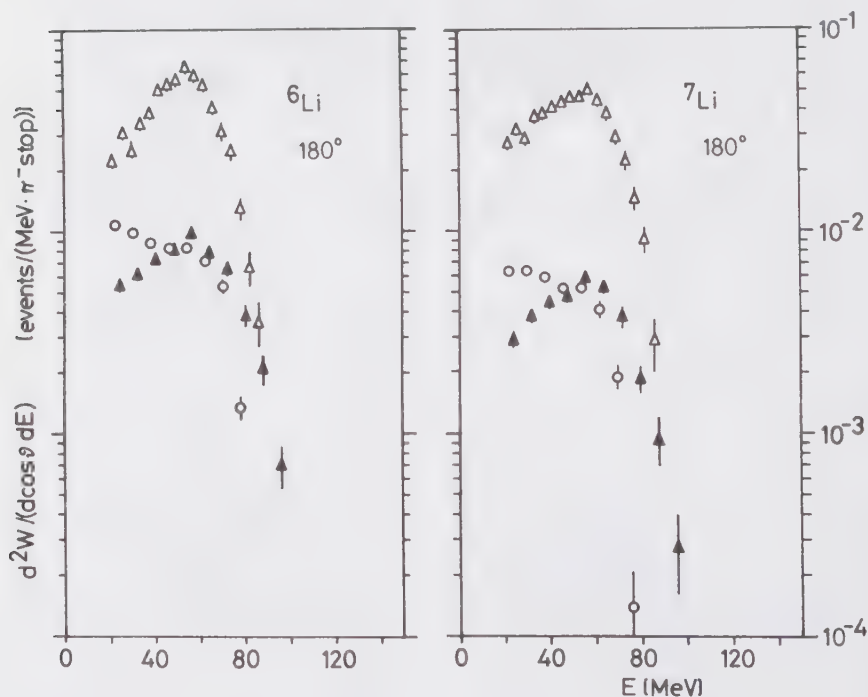


Fig. 4.1.3. Energy spectra of neutrons emitted in $n - n$ coincidences (open triangles, $E_{n2} > 20$ MeV, [Isa82]), and energy spectra of protons (open circles, $E_n > 20$ MeV) and neutrons (full triangles, $E_p > 20$ MeV) emitted in $n - p$ coincidences after pion absorption on s-shell nucleons in ${}^6\text{Li}$ and ${}^7\text{Li}$. Particle emission from s-shell nucleons is defined in figs. 4.1.1. and 4.1.2. The errors are statistical only, the error of the normalization is 15%.

n - n events from s-shell absorption are both broader as compared to those of the p-shell absorption.

Since the p-shell of the lithium nuclei is occupied by only one proton, the emission of an n - p pair always must involve s-shell nucleons. The ratio $R(\text{p-shell})$ of np to pp pairs that can absorb the pion is therefore infinite, and thus the n - p spectrum (figs. 4.1.1. and 4.1.2.) has to be compared with that part of the n - n spectrum which is produced by s-shell absorption. The two-dimensional energy spectrum does not show any clear enhancement arising from direct emission of an n - p pair after quasi-free absorption on a pp pair. Nevertheless in order to extract the value $R(\text{s-shell})$, energy spectra (fig. 4.1.3.) and opening angle distributions (fig. 4.1.4.) of n - p pairs from s-shell absorption are compared with those of n - n pairs. The proton spectra of the n - p coincidences (fig. 4.1.3.) for s-shell absorption have different shapes compared to the corresponding neutron spectra. The enhancement at low proton energies may be due to a contamination of the n - p spectra by secondary particles stemming from primary n - n events, where one of the neutrons lost energy by a knock on or by a charge exchange reaction. Because of this contamination in the n - p spectra the values for R obtained by this method are lower limits only. Both values $R(\text{s-shell}) > 4.4$ for ${}^6\text{Li}$ and $R(\text{s-shell}) > 7.8$ for ${}^7\text{Li}$ are considerably higher than the statistical ratios for absorption involving s-shell nucleons (2.7 and 3.3, respectively)

In figs. 4.1.4. and 4.1.5. the shapes of the opening angle distributions and energy spectra of n - n events emitted after pion absorption on p-shell nucleons in ${}^6\text{Li}$ and ${}^7\text{Li}$ are compared to the calculated shapes using a Gaussian momentum distribution for the absorbing quasi-deuteron. The width parameter γ of the Gaussian is 50 MeV/c for ${}^6\text{Li}$ and 100 MeV/c for ${}^7\text{Li}$. For ${}^6\text{Li}$ this value corresponds to a harmonic oscillator parameter $\beta = \sqrt{\hbar/m\omega}$ of 4.55 fm. γ describes the width of the momentum

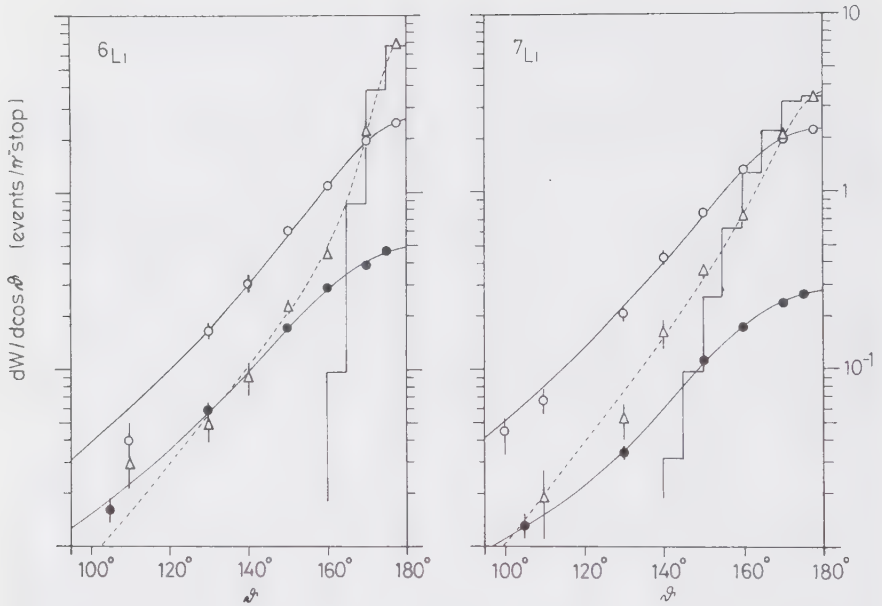


Fig. 4.1.4. Opening angle distribution of $n - n$ events [Isa82] (triangles: absorption on p-shell nucleons; open circles: absorption on s-shell nucleons), and of $n - p$ events (full circles: absorption on s-shell nucleons), emitted after pion absorption in ${}^6\text{Li}$ and ${}^7\text{Li}$ ($E_1, E_2 > 20$ MeV). p-shell and s-shell absorption are defined in figs. 4.1.1. and 4.1.2. The errors are statistical only, the error in the normalization is 15 %. The lines are the fits for the integration. The histograms show the calculated distribution (normalized at 180°) using $\gamma = 50$ MeV/c for ${}^6\text{Li}$ and $\gamma = 100$ MeV/c for ${}^7\text{Li}$.

distribution of the absorbing np pair relative to the residual nucleus; it was taken from ref. [Alb80], who investigated the reaction ${}^6\text{Li}(p, pd){}^4\text{He}$. For ${}^7\text{Li}$ the value $\gamma = 100$ MeV/c ($\beta = 2.35$ fm) describes the momentum distribution between the absorbing deuteron-cluster and the residual ${}^5\text{He}$ -cluster. Because no data are available, the same value for β was used as for the calculation of the $n - t$ spectrum (see sect. 4.2.). The agreement between measured and calculated shapes of the opening

angle distribution and energy spectra is reasonably good. The value of γ for ${}^6\text{Li}$ seems to be somewhat too small. The differences between the measured and calculated opening angle distribution at smaller angles may be explained by elastic final state interactions of one of the primary nucleons with the residual nucleus. Part of the final state interactions, e.g. scattering processes of a primary particle with the residual α -cluster, may happen without excitation of the residual nucleus, and hence cannot be identified by their recoil corrected sum energy E_S . Probabilities for the occurrence of large recoil momenta higher than predicted by the simple model may as well explain part of the deviations.

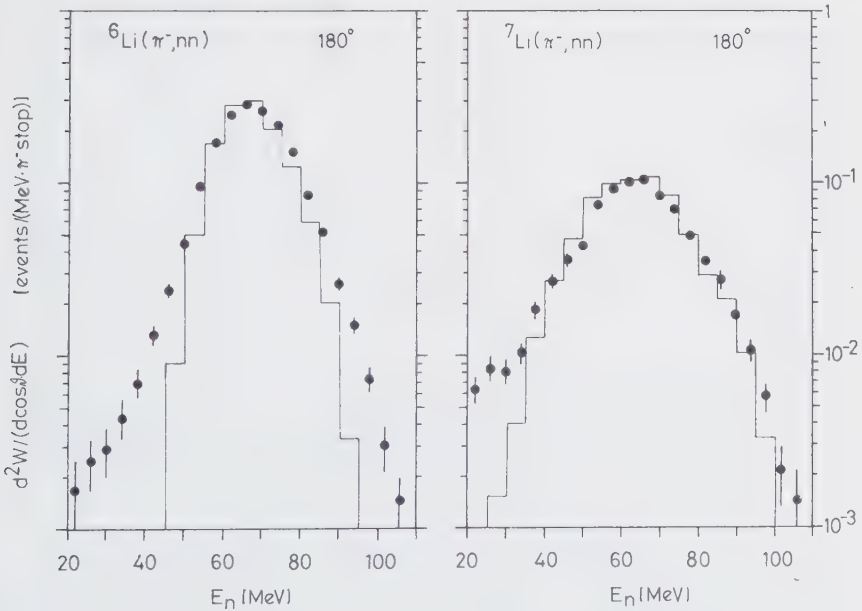


Fig. 4.1.5. Energy spectra of neutrons emitted in $n - n$ coincidences after pion absorption on p-shell nucleons (see figs. 4.1.1. and 4.1.2.) in ${}^6\text{Li}$ and ${}^7\text{Li}$ ($E_{n2} > 20$ MeV, [Isa82]). The histograms show the calculated spectra (normalized to the experimental ones) using $\gamma = 50$ MeV/c for ${}^6\text{Li}$ and $\gamma = 100$ MeV/c for ${}^7\text{Li}$. The errors are statistical only, the error of the normalization is 15%.

The total yields obtained by integrating the opening angle distributions for energy thresholds of 20 MeV are given in table 4.1. A comparison of the present results with those obtained by Nordberg et al. [Nor68] for ${}^6\text{Li}$ and ${}^7\text{Li}$ shows that the present values are in agreement within the large errors of the old measurement. The second measurement of Nordberg et al., with finer angular resolution, however, is in disagreement with the present results. Their opening angle distribution of $n - p$ coincidences emitted after pion absorption in ${}^6\text{Li}$ (fig. 4.1.6.) was therefore renormalized to our data. The comparison of the shapes gives reasonably good agreement.

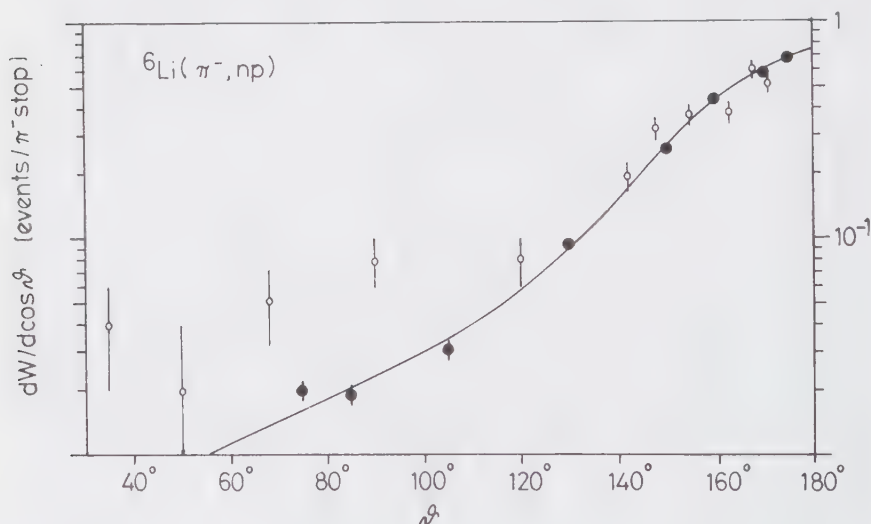


Fig. 4.1.6. Opening angle distribution of coincident neutron - proton pairs ($E_n, E_p > 20$ MeV) emitted after pion absorption in ${}^6\text{Li}$. The full circles show the present data, the open circles are from Nordberg et al. [Nor68] and are renormalized to our data. The errors given for the present data are statistical only, the error of the normalization is 15%. The solid line is the fit used for the integration.

Table 4.1.

Yields of neutron - neutron and neutron - charged particle coincidences with $E_1, E_2 > 20$ MeV for pion absorption in ${}^6\text{Li}$ and ${}^7\text{Li}$. Yields for quasi-free absorption on quasi-deuterons (p-shell and s-shell nucleons, see figs. 4.1.1. and 4.1.2.), ${}^3\text{He}$ and α -clusters (see figs. 4.2.1. and 4.2.6.) are also given. c - c is the total yield of charged particle - charged particle coincidences (p, d, t) obtained by ref. [Sen82].

emitted particles	absorption mechanism	Yield ($/\pi$ - stop) ${}^6\text{Li}$ ${}^7\text{Li}$		Ref.
n-n	all	0.51(9)	0.61(10)	[Isa82] <u>a</u>
n-n	p-shell nucleons	0.16(3)	0.18(3)	[Isa82]
n-n	s-shell nucleons <u>b</u>	0.28(5)	0.34(5)	[Isa82]
n-p	all	0.132(20)	0.096(15)	this work
n-p	all	0.11(3)	0.13(4)	[Nor68]
n-p	all	0.23(6)		[Nor68] <u>c</u>
n-p	s-shell nucleons <u>b</u>	0.083(13)	0.053(8)	this work
n-d	all	0.139(21)	0.107(16)	this work
nn-d <u>d</u>	α -cluster	0.013(2)	0.011(2)	this work
n-d	${}^3\text{He}$ -cluster	0.086(13)	0.055(8)	this work
n-t	all	0.086(13)	0.088(13)	this work
n-t	α -cluster	0.078(12)	0.068(11)	this work
c-c	all	0.042(5)	0.034(4)	[Sen82]

a These values are in agreement with other measurements. For detailed comparison see ref. [Isa82].

b Two s-shell nucleons or one p-shell and one s-shell nucleon.

c Measurement with finer angular resolution [Nor68].

d Only one neutron is detected (see also fig. 4.2.6.).

4. 2. ABSORPTION ON HEAVIER CLUSTERS

In fig. 4.2.1. the two-dimensional energy spectra of coincident neutron - triton pairs emitted after pion absorption in ${}^6\text{Li}$ and ${}^7\text{Li}$ are shown. As expected from the two-body breakup reaction of an α -particle, the emitted triton has $1/4$ and the neutron $3/4$ of the available energy of $Q({}^6\text{Li}(\pi^-, nt){}^2\text{H}) = 117 \text{ MeV}$ and $Q({}^7\text{Li}(\pi^-, nt){}^3\text{H}) = 116 \text{ MeV}$. The quasi-free kinematics is very well fulfilled. The tail in the spectrum of ${}^7\text{Li}$ towards higher triton energies and lower neutron energies indicates contributions from other reaction channels. In ${}^6\text{Li}$ these contributions are less than 10% of the maximum of the $n - t$ peak and hence not visible in the figure. In fig. 4.2.2. the projections of the two-dimensional energy distribution for ${}^6\text{Li}$ are shown. The triton spectrum exhibits a narrow peak at 29 MeV and the neutron spectrum peaks around 85 MeV. The width of the peak in the neutron spectrum is mainly determined by the energy resolution at these high neutron energies (see also fig. 3.3.3.). The triton spectrum is well reproduced by our simple model calculation. The same value of $\gamma = 50 \text{ MeV}/c$ was used here as in the calculation of the $n - n$ spectrum, because in both cases the matrix element depends on the relative momentum of the absorbing deuteron and the residual ${}^4\text{He}$ or absorbing ${}^4\text{He}$ -cluster and residual deuteron (assuming that the absorbing α -cluster consists of s -shell nucleons). The calculated neutron spectrum is also shown. After folding this spectrum with the experimental resolution, good agreement is obtained. The shoulder at 50 MeV in the triton spectrum may be attributed to processes where the whole ${}^6\text{Li}$ nucleus is involved in the absorption process. In this case a high energy triton and an $n - d$ pair is emitted back to back. In ref. [Sen82] indications for a very broad resonance in the $n - d$ system were found from the observation of deuteron - triton coincidences. The position of the shoulder is in qualitative agreement with this assumption.

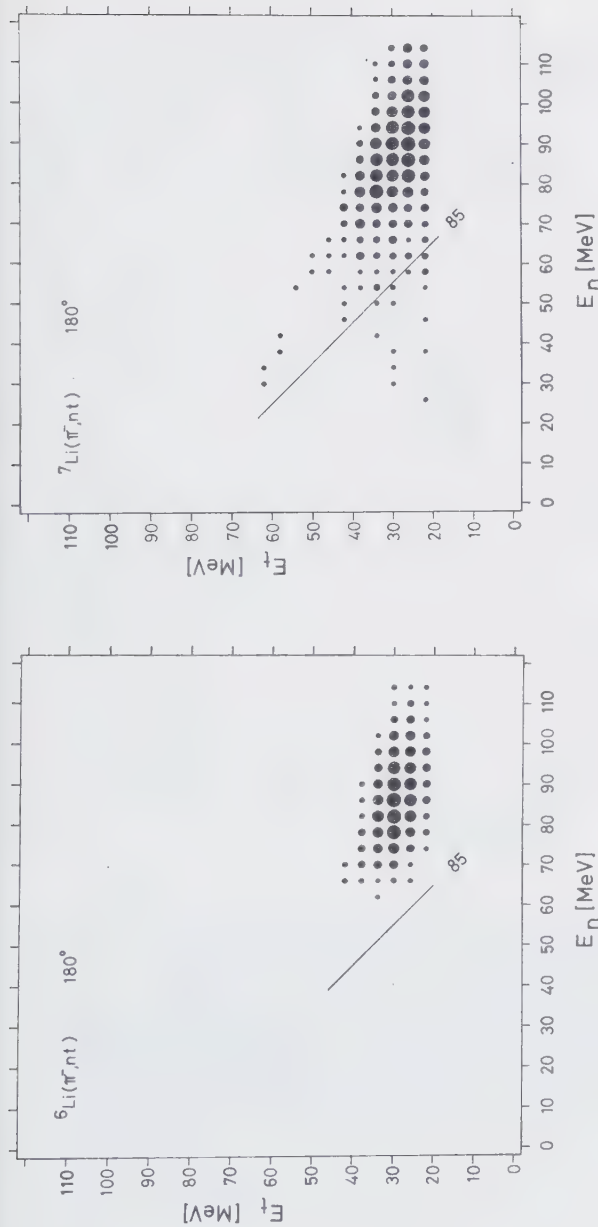


Fig. 4.2.1. Two-dimensional energy spectra $d^3W/dE_n dE_t d\cos\theta$ ($\theta = 180^\circ$) of neutron-triton pairs emitted after pion absorption in ${}^6\text{Li}$ and ${}^7\text{Li}$ ($E_n, E_t > 20$ MeV). The maximum of the ${}^6\text{Li}$ distribution is by a factor of 5 higher than the maximum of the ${}^7\text{Li}$ distribution. n^-t events from quasi-free absorption on an α -cluster are defined by $E_n > 85$ MeV. In appendix B the spectra are also given numerically. (See also fig. 4.1.1.).

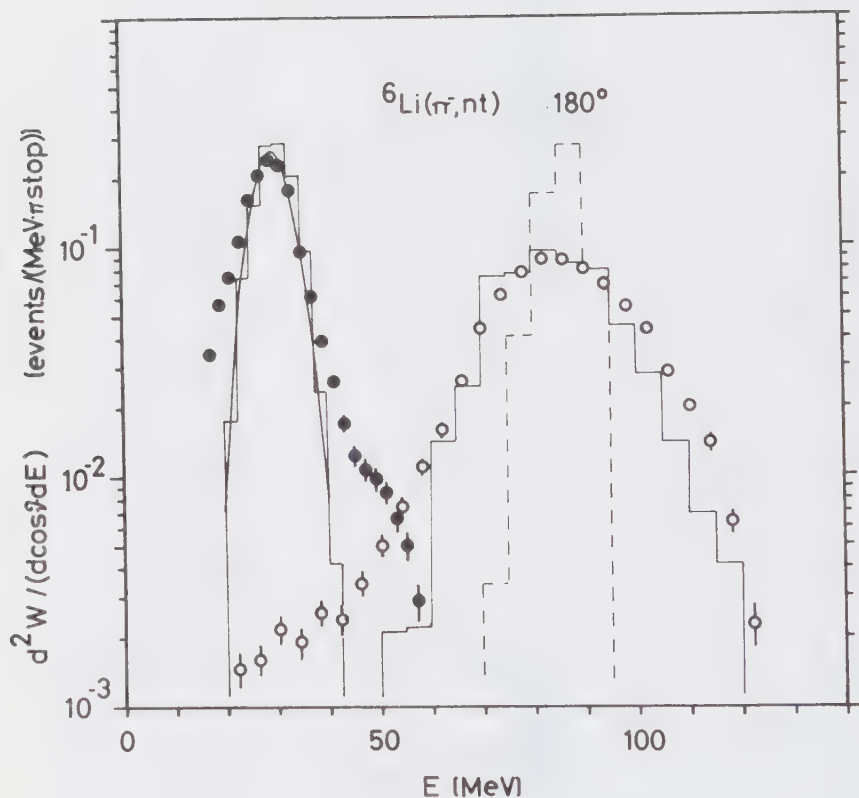


Fig. 4.2.2. Energy spectra of neutrons (open symbols, $E_t > 20$ MeV) and tritons (full symbols, $E_n > 20$ MeV) emitted in neutron - triton coincidences after pion absorption on an α -cluster (see fig. 4.2.1.) in ${}^6\text{Li}$. The errors are statistical only, the error of the normalization is 15%. The histograms show the model calculation using the parameter $\gamma = 50$ MeV/c ($\beta = 4.55$ fm). The dashed histogram is the neutron spectrum calculated without the experimental energy resolution, the curve is the analytical calculation, neglecting the small recoil energy (see sect. 2.3., eq. 5).

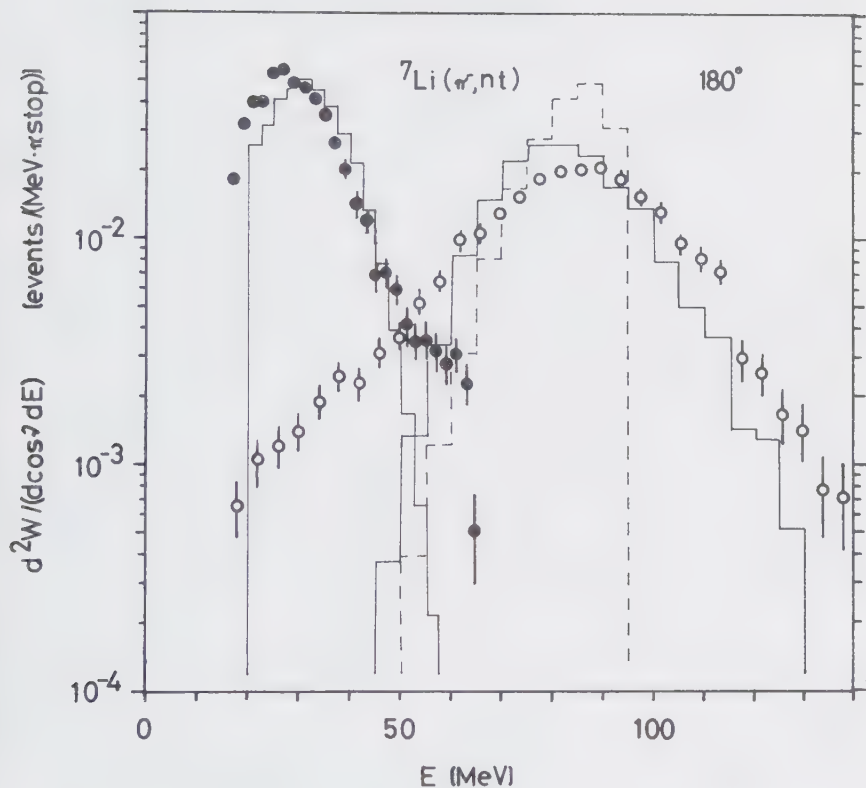


Fig. 4.2.3. Energy spectra of neutrons (open symbols, $E_t > 20$ MeV) and tritons (full symbols, $E_n > 20$ MeV) emitted in neutron triton coincidences after pion absorption on an α -cluster (see fig. 4.2.1) in ${}^7\text{Li}$. The errors are statistical only, the error of the normalization is 15%. The histograms show the model calculation using the parameter $\gamma = 109.5$ MeV/c ($\beta = 2.35$ fm). The dashed histogram is the neutron spectrum calculated without correction for the experimental energy resolution.

To demonstrate the validity of the simple analytical expression given in sect. 2.3., the analytical calculation is also shown in fig. 4.2.2.

Fig. 4.2.3. shows the triton and neutron spectra for ${}^7\text{Li}$ (projections of the two-dimensional energy spectra, fig. 4.2.1.). The triton peak is much broader than that for ${}^6\text{Li}$, accounting for the stronger binding of the $\alpha - t$ clusters in ${}^7\text{Li}$. The model calculation with $\gamma = 109.5 \text{ MeV/c}$ ($\beta = 2.35 \text{ fm}$) is also shown in fig. 4.2.3. This value for γ is obtained by fitting the experimental $\alpha - t$ momentum distribution measured in the ${}^7\text{Li}(p, p\alpha)t$ reaction [Jai70] (see fig. 4.2.4.). The agreement between measured and calculated energy spectrum is not as good as in the case of ${}^6\text{Li}$. There is a lack of tritons with energies around 25 MeV and of the corresponding neutrons at very high energies. To test whether or not this deviation is due to the fact that the measured $\alpha - t$ momentum distribution has a minimum at zero momentum, the calculation was also done using a Gaussian centered at 45 MeV/c (see fig. 4.2.4.). No improvement in the

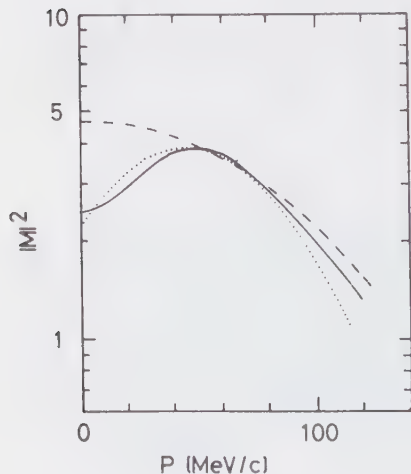


Fig. 4.2.4. Momentum distribution extracted from the ${}^7\text{Li}(p, p\alpha)t$ data from ref. [Jai70] (solid line) compared to the Gaussian momentum distribution (dashed line) with $\gamma = 109.5 \text{ MeV/c}$ ($\beta = 2.35 \text{ fm}$) and with a Gaussian distribution (dotted line) of the form

$$\sim \exp -\left(\frac{P-45}{60}\right)^2$$

spectrum was achieved using this momentum dependence of the matrix element. The deviation may however be explained by final state correlations between the primary and the residual triton. The high energy shoulder in the triton spectrum may be explained by absorption processes involving the whole nucleus; e.g. high energy tritons from the reaction ${}^7\text{Li}(\pi^-, t){}^4\text{H}$, ${}^4\text{H} \rightarrow n + t$ [Sen81].

In fig. 4.2.5. the opening angle distributions of $n - t$ pairs from quasi-free absorption on an α -cluster (see fig. 4.2.1.) are shown and compared to our model calculation. The agreement is reasonably good. The distribution for ${}^6\text{Li}$ is very sharp but

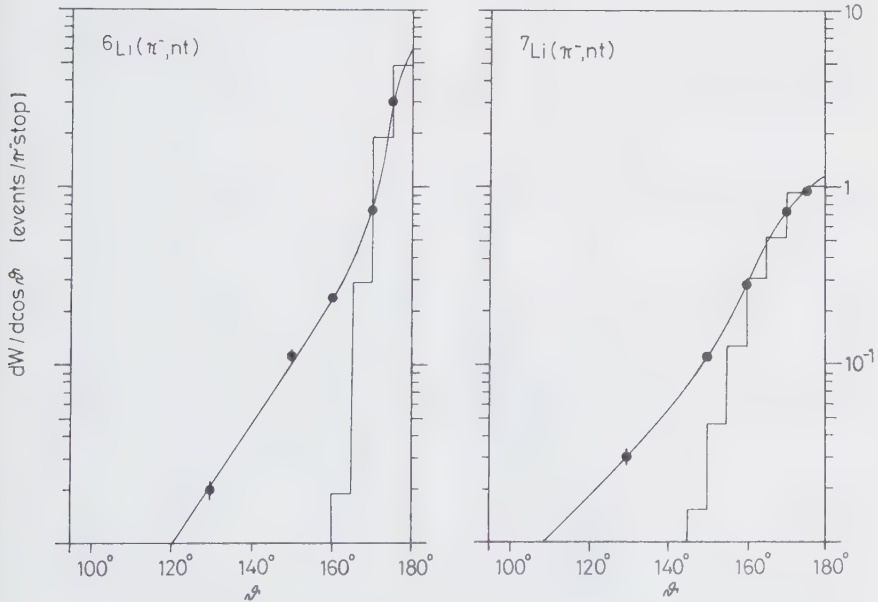


Fig. 4.2.5. Opening angle distribution of $n - t$ pairs emitted after quasi-free pion absorption on an α -cluster (see fig. 4.2.1.) in ${}^6\text{Li}$ and ${}^7\text{Li}$ ($E_\pi, E_t > 20$ MeV). The errors are statistical only, the error of the normalization is 15%. The solid lines are the fits used for the integration. The histograms show the distribution obtained by the model calculation with $\gamma = 50$ MeV/c for ${}^6\text{Li}$ and $\gamma = 109.5$ MeV/c for ${}^7\text{Li}$.

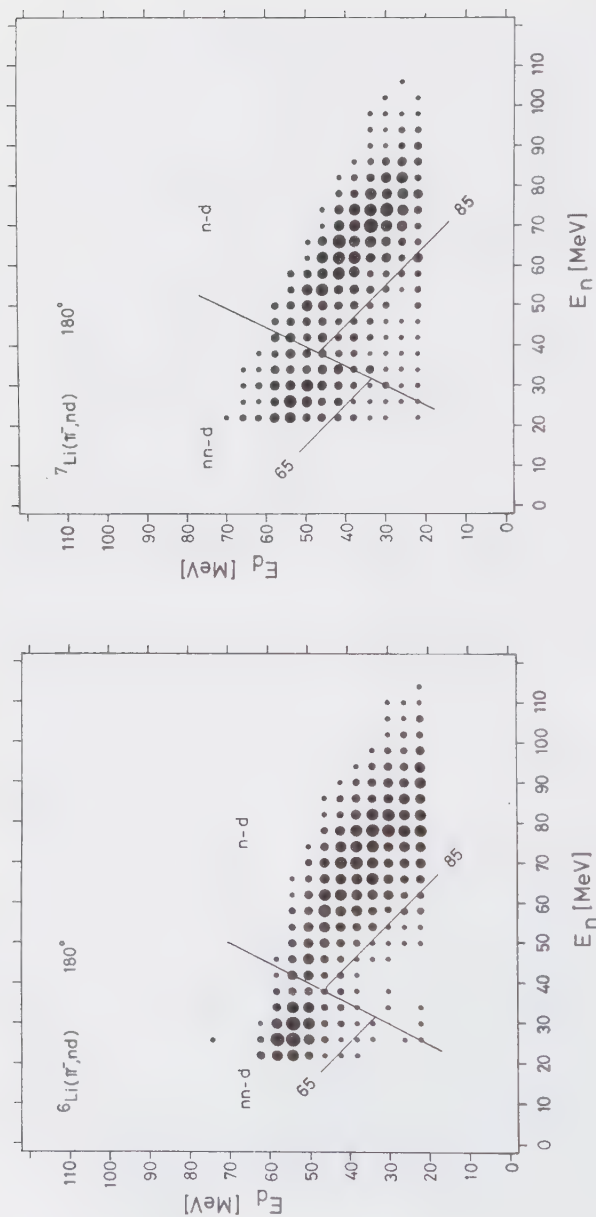


Fig. 4.2.6. Two-dimensional energy spectra $d^3W/dE_n dE_d \cos\theta$ ($\theta = 180^\circ$) of neutron - deuteron pairs emitted after pion absorption in ${}^6\text{Li}$ and ${}^7\text{Li}$ ($E_n, E_d > 20\text{MeV}$). Events stemming from quasifree pion absorption on an α -cluster ($nn-d$ channel) are defined by $E_s > 65$ MeV and $E_d > 2E_n - 30$ MeV (thick solid line). Events stemming from pion absorption on a ${}^3\text{He}$ -cluster ($nn-d$ channel) are defined by $E_s > 85$ MeV and $E_d < 2E_n - 30$ MeV. The maximum of the ${}^6\text{Li}$ distribution is by a factor of 1.7 higher than the maximum of the ${}^7\text{Li}$ distribution. In appendix B the spectra are also given numerically. (See also fig. 4.1.1.).

the angular resolution of the apparatus is not sufficient to determine the exact shape near 180° . At opening angles smaller than 150° the distribution is probably influenced by final state interactions.

The emission of $n - d$ pairs may also give evidence for absorption on heavier clusters. The two-dimensional energy spectra measured at an opening angle of 180° are shown in fig. 4.2.6. Both spectra show two enhancements, a rather sharp peak around $E_n = 28$ MeV and $E_d = 56$ MeV, and a broad enhancement with 70 MeV neutron energy and 35 MeV deuteron energy. The first of these maxima can be explained by the following mechanism: the pion is absorbed by an α -cluster, leading to the emission of a deuteron with $E_d = Q/2$, and two neutrons, flying in parallel (or with a very small opening angle) in the opposite direction. Each of the neutron then has $E_n = Q/4$. In what follows, these events are labelled $nn - d$ events. In fig. 4.2.7. the neutron and deuteron energy spectra of these events are shown. The shapes of the deuteron spectra are reproduced by the model calculations using the same parameters β as before. For the calculation it is assumed that the two neutrons behave as one single particle with a mass of twice the neutron mass. The calculated neutron spectrum is obtained using $E_n = E_{nn}/2$. It is apparent that the width of the calculated neutron spectra is too small. This discrepancy can be explained by a small relative momentum of the two neutrons. The same effect causes also the small shift of the deuteron spectrum to lower energies.

The second maximum with 70 MeV neutron energy and 35 MeV deuteron energy is also produced by absorption processes on more than two nucleons. Most of the available energy is shared by the three nucleons in the $n - d$ pair; the neutron carries $2/3$ and the deuteron $1/3$ of the Q -value, as expected from quasi-free absorption on a ${}^3\text{He}$ -cluster. The recoil momenta, however, seem to be much higher than in the case of $n - t$ or $nn - d$ emission, giving rise to a smearing in the direction of constant $E_d + E_n$.

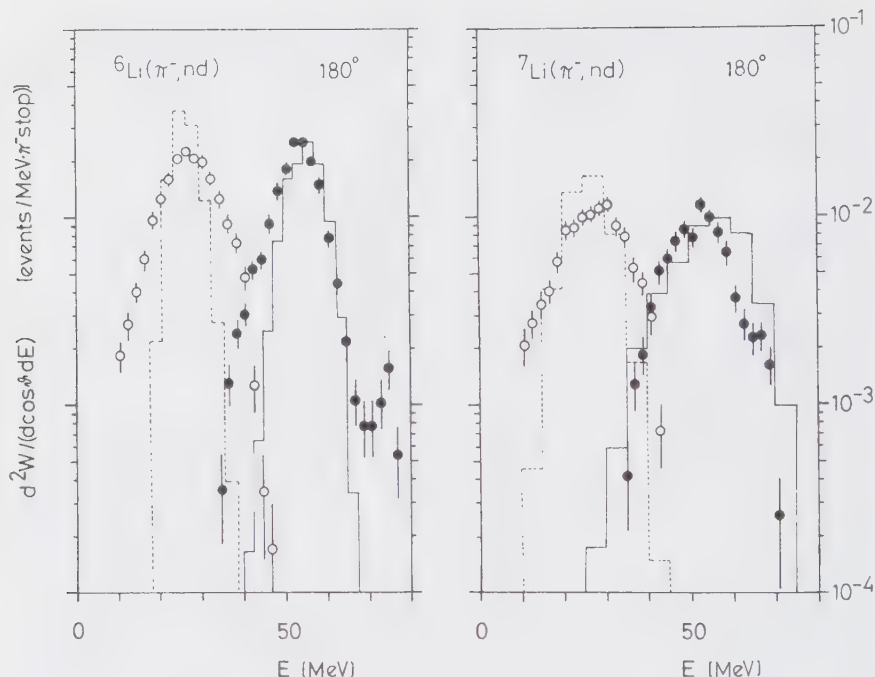


Fig. 4.2.7. Energy spectra of neutrons (open circles, $E_d > 20$ MeV) and deuterons (full circles, $E_n > 20$ MeV) emitted in neutron - deuteron coincidences (nn - d events, see fig. 4.2.6.) after quasi-free absorption on an α -cluster in ${}^6\text{Li}$ and ${}^7\text{Li}$. The errors are statistical only, the error of the normalization is 15%. The histograms show the spectra calculated by the simple model (see text).

In figs. 4.2.3. and 4.2.9. the neutron and deuteron energy spectra of these n - d events are shown. The opening angle distributions are given in fig. 4.2.10.

The yields of n - d and n - t coincidences emitted after pion absorption in ${}^6\text{Li}$ and ${}^7\text{Li}$ are given in table 4.1. Adding the yields of direct n - t and nn - d emission after pion absorption on an α -cluster gives an estimate for the probability $W(\alpha)$ for pion absorption on an α -cluster (i.e. absorption on four nucleons). These probabilities are 0.091 ± 0.013 / π -stop for

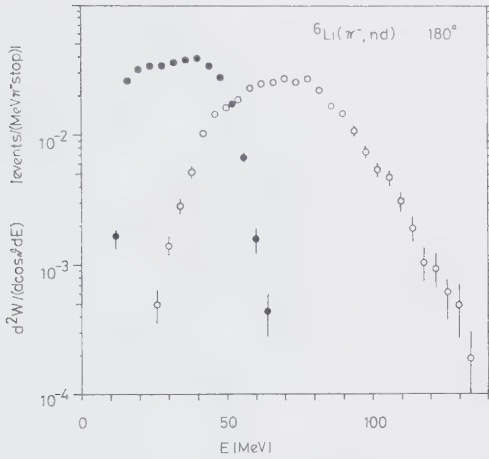


Fig. 4.2.8. Energy spectra of neutrons (open circles, $E_d > 20$ MeV) and deuterons (full circles, $E_n > 20$ MeV) emitted in neutron - deuteron coincidences ($n-d$ events, see fig. 4.2.6) after quasi-free absorption on a ${}^3\text{He}$ -cluster in ${}^6\text{Li}$. The errors are statistical only, the error of the normalization is 15%.

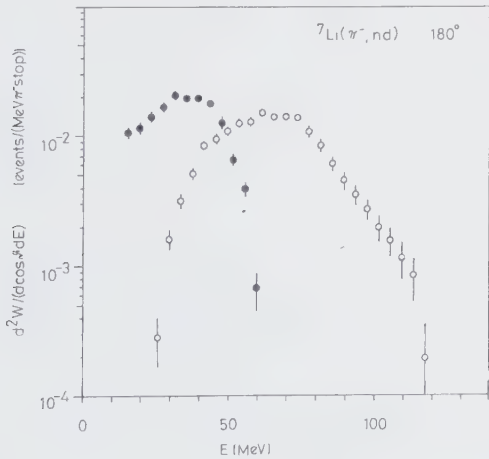


Fig. 4.2.9. Energy spectra of neutrons (open circles, $E_d > 20$ MeV) and deuterons (full circles, $E_n > 20$ MeV) emitted in neutron - deuteron coincidences ($n-d$ events, see fig. 4.2.6.) after quasi-free absorption on a ${}^3\text{He}$ -cluster in ${}^7\text{Li}$. The errors are statistical only, the error of the normalization is 15%.

${}^6\text{Li}$ and 0.079 ± 0.011 / π -stop for ${}^7\text{Li}$. These values are lower limits, because events where the emitted particles underwent final state interactions are not considered. The spectrum of deuterons emitted after pion absorption in ${}^4\text{He}$ shows a pronounced peak at very low deuteron energies [Zio70]. It is therefore clear that for pion absorption in ${}^4\text{He}$, the quasi-deuteron mechanism is also important. From the single deuteron and triton spectrum of ref.[Zio70], the ratio $W(nn - d)/W(n - t)$ for ${}^4\text{He}$ was estimated to be 0.25 ± 0.08 . To separate the $nn - d$ channel in the single deuteron spectrum from the other channels the $n - d$ coincidence measurement of ref. [Bar73] has been used. The measured ratios $W(nn - d)/W(n - t)$ for ${}^6\text{Li}$ and ${}^7\text{Li}$ are $0.17(4)$ and $0.16(4)$, respectively. Within the large uncertainties of the extraction of the relevant data from the papers of refs. [Zio70] and [Bar73] the ratios for ${}^4\text{He}$ and ${}^6\text{Li}$ and ${}^7\text{Li}$ are the same.

The total yield of particle pairs, with a lower threshold of 20 MeV on the energies of both emitted particles is 0.91 ± 0.11 / π -stop for ${}^6\text{Li}$ and 0.94 ± 0.11 / π -stop for ${}^7\text{Li}$ (from table 4.1.). These values are near to 1.0, which means that almost every absorption process is followed by the emission of a high energy pair. Addition of the yields of the primary particles emitted without final state interactions gives a total yield of 0.70 ± 0.07 / π -stop for ${}^6\text{Li}$ and 0.71 ± 0.07 / π -stop for ${}^7\text{Li}^*$. In about 2/3 of all absorption processes the primary particles are therefore emitted with no or very small final state interaction with the residual nucleus.

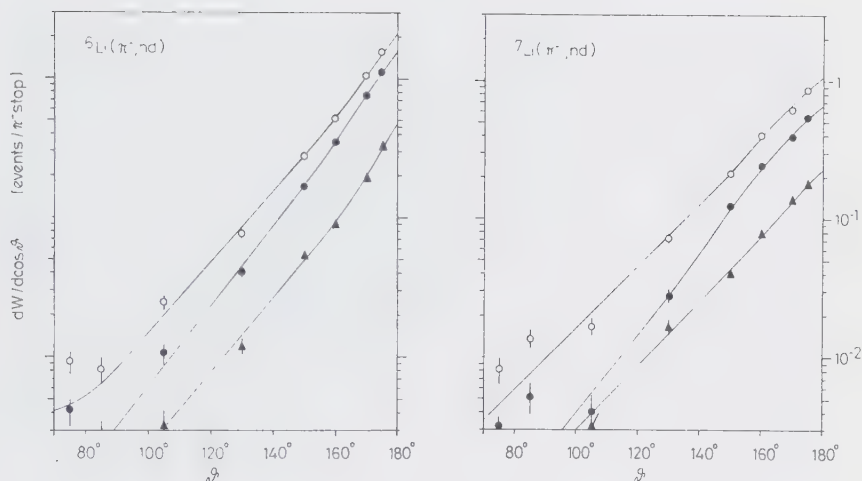


Fig. 4.2.10. Opening angle distribution of neutron deuteron pairs emitted after pion absorption in ${}^6\text{Li}$ and ${}^7\text{Li}$. Open circles give the distribution of all events with $E_n, E_d > 20$ MeV; the full circles show the distribution of the $n-d$ events and the full triangles that of the $nn-d$ events (see fig. 4.2.6.). The errors are statistical only, the error in the normalization is 15%. The solid lines are the fits used for the integration.

* The difference of about $0.2 / \pi\text{-stop}$ of processes with final state interaction includes processes where three particles are emitted with energies above the thresholds. In this case the detection probability of a particle pair is enhanced. A rough estimate of the effect lowers the difference to $0.15 / \pi\text{-stop}$, resulting in a total yield of about $0.85 / \pi\text{-stop}$

5. PION ABSORPTION IN ^{12}C , ^{59}Co AND ^{197}Au

In the previous chapter it has been shown that for pion absorption in ^6Li and ^7Li the final state interactions with the residual nucleus are of minor importance. The spectra of the particles emitted after pion absorption in ^{12}C show that for this nucleus the direct emission and emission after final state interactions are both considerable. The separation of the direct emission allows the investigation of the pion absorption process without requiring a model for the pre-equilibrium stage. For the heavier nuclei ^{59}Co and ^{197}Au , however, the spectra of the emitted particles are completely determined by the final state interactions. In sect. 5.1. and 5.2. absorption on quasi-deuterons and the absorption on heavier clusters in ^{12}C is studied, whereas sect. 5.3. gives the results on ^{59}Co and ^{197}Au .

5. 1. ABSORPTION ON QUASI-DEUTERONS IN ^{12}C

Fig. 5.1.1. shows the two-dimensional energy spectra of neutron - neutron and neutron - proton pairs emitted at an opening angle of 180° after the absorption of stopped negative pions in ^{12}C . The strong maximum in the n - n spectrum is produced by neutron - neutron pairs emitted after the quasi-free absorption on a np pair. The total energy $E_{n1} + E_{n2} + E_R$ agrees with the Q-value of 111.7 MeV of the reaction $^{12}\text{C}(\pi^-, nn)^{10}\text{B}$. The structure in the n - p spectrum stemming from the quasi-free absorption on a pp pair ($^{12}\text{C}(\pi^-, np)^{10}\text{Be}$), $Q = 111.1$ MeV) is less pronounced. The neutron energy resolution does not allow separation of transitions to the ground state of the residual nucleus from those to the low lying excited states. Due to the Fermi motion of the absorbing pair, the peaks are broadened in the direction of constant $E_1 + E_2$. In contrast to the spectra for lithium, no second enhancement resulting from pion absorption involving s-shell nucleons is observed.

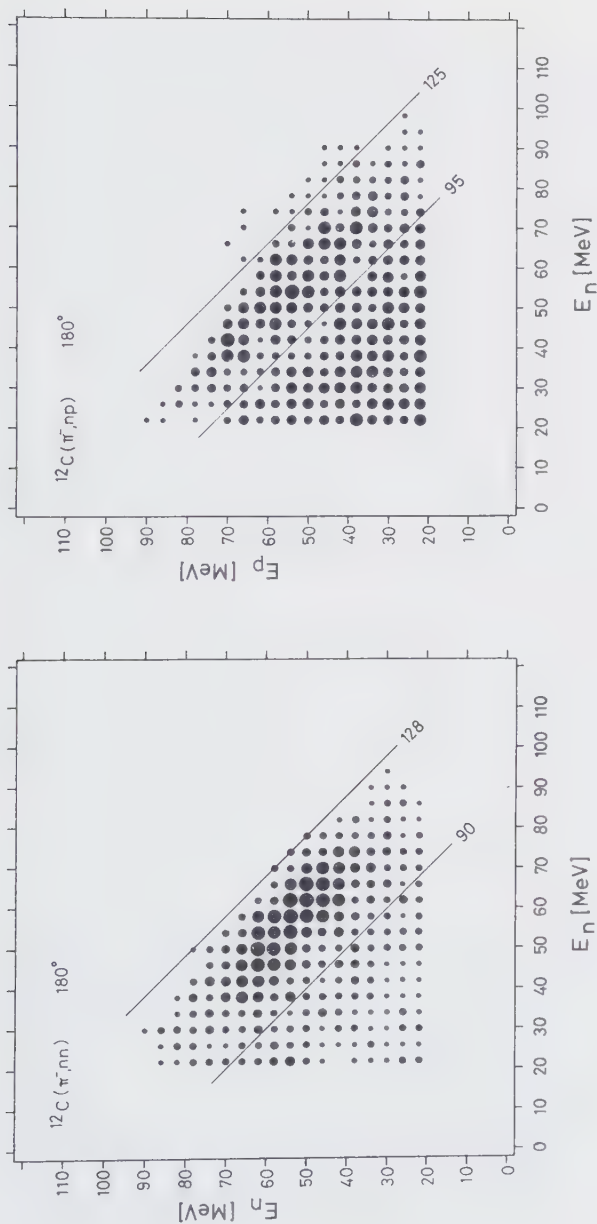


Fig. 5.1.1. Two-dimensional energy spectra $d^3W/dE_dE_d\cos\theta$ ($\theta = 180^\circ$) of neutron - neutron [Isa82] and neutron - proton pairs emitted after pion absorption in ^{12}C ($E_n, E_p > 20$ MeV). The maximum of the $n - p$ distribution is by a factor of 4.5 lower than that of the $n - n$ distribution. Events from quasi-free absorption on p-shell nucleons (primary events) were defined by the condition $90 < E_s < 128$ MeV ($n - n$) and $95 < E_s < 125$ MeV ($n - p$). All other events are defined as secondary events. In appendix B the spectra are also given numerically. (See also fig. 4.1.1.).

By means of cuts on the sum energy $E_1 + E_2 + E_R$ the pairs emitted after quasi-free absorption in the p-shell of ^{12}C (primary pairs) can be separated from those where at least one of the nucleons underwent final state interaction with the residual nucleus (secondary pairs). By comparing the intensities in the quasi-free peaks, the ratio R of np to pp pairs that absorb the pion can be obtained for the p-shell of ^{12}C . The comparison is done for the angular range of $160^\circ - 180^\circ$ and gives $R(\text{p-shell}) = 6.3 \pm 1.4$. This value is by more than a factor of two larger than the statistical ratio $R_{\text{st}} = 2.7$ of np to pp pairs in the p-shell of ^{12}C . Thus, for a given np or pp pair in the p-shell of the carbon nucleus the absorption width for the np pair is about twice the width for the pp pair. Lee et al. [Lee72] obtained a ratio $R = 16 \pm \frac{8}{3}$ for pion absorption in the p-shell, by comparing their n - p yield with the n - n yield of Cheshire and Sobottka [Che69], in the angular range $170^\circ - 180^\circ$. The deviation in the value for R is mainly due to a factor two discrepancy in the n - n yields of ref. [Che69] and ref. [Isa82] (see ref. [Isa82]). The value $R = 2.5 \pm 1.0$ of Nordberg et al. [Nor68] is the ratio of the total yields of n - n and n - p pairs, with thresholds of about 20 MeV on the energy of the emitted particles. These yields include pairs losing energy in final state interactions. Our measured ratio of n - n to n - p pairs for $E_n, E_p > 20$ MeV is 3.5 ± 0.8 (see table 5.1.) and agrees with the value of Nordberg et al.

The energy spectra of primary neutron - neutron and neutron - proton pairs are shown in fig. 5.1.2. The shapes of the spectra are similar. The excess of low energy protons and therefore of high energy neutrons, may be explained by secondary events in the spectrum of primary n - p pairs. These secondary events arise from charge exchange reactions of primary n - n events*.

In fig. 5.1.3. the spectrum of neutrons emitted in n - n pairs after pion absorption in ^{12}C is compared with results of model calculations. The shape of the spectrum of primary neutrons is

well reproduced by the simple model calculation with a matrix element $M \sim \exp(-P^2/\gamma^2)$. The value of $\gamma = 160$ MeV/c is derived from the harmonic oscillator parameter given by refs. [Ber78, Jas74]. This value also agrees with the parameters used in ref. [Kho81] for the description of the momentum distribution of quasi-deuterons in the p-shell of the carbon nucleus. These parameters were determined analysing the reaction $^{12}\text{C}(\gamma, np)^{10}\text{B}$. The energy spectrum of primary neutrons calculated by Chiang and Hufner [Chi81] is also shown in fig. 5.1.3. The width of the enhancement at 60 MeV is too broad and corresponds to a γ of about 300 MeV/c. The measured energy spectrum of secondary neutrons [Isa82] is compared with the energy spectrum of secondary neutrons calculated in the intranuclear cascade calculation of Chiang and Hufner. The agreement between calculated and measured spectra is better for the secondary than for the primary ones.

The shape of the opening angle distributions of primary n - n and n - p pairs (fig. 5.1.4.) is well described by our simple model calculation. The differences at angles smaller than 150° may be explained by final state interactions of the primary nucleons

* Nyman [Nym73] postulated an energy shift between the neutron and the proton energy spectra due to different potential wells for the outgoing neutrons and protons. For pion absorption in carbon, the centroid of the neutron spectrum was expected to be 7 to 13 MeV higher than that of the proton spectrum. As a confirmation, the author quoted the measurement of ref. [Cal70] who observed a very large shift for pion absorption on ^9Be , in agreement with the calculation (26 MeV). Since in the same experiment the shift for ^{12}C was found to be larger than 30 MeV, and the observed proton spectrum is in disagreement with other work, there exist some doubts on the quality of that measurement. Nyman's prediction can be tested reliably by re-measuring pion absorption in ^9Be .

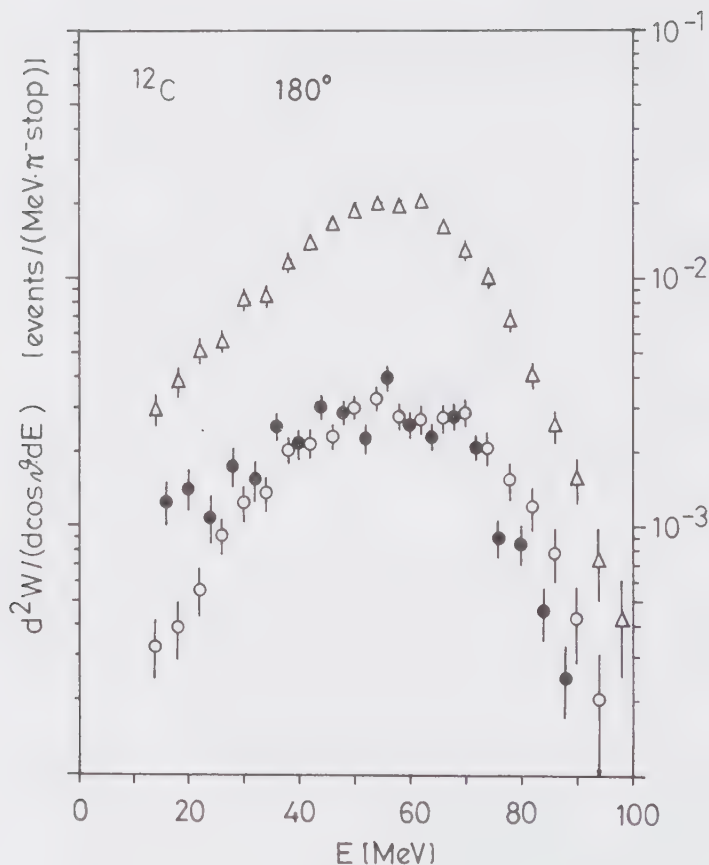


Fig 5.1.2. Energy spectrum of neutrons emitted in n - n coincidences (open triangles, $E_{n2} > 20$ MeV, [Isa82]) and energy spectrum of protons (full circles, $E_n > 20$ MeV) and neutrons (open circles, $E_p > 20$ MeV) emitted in n - p coincidences after quasi-free pion absorption on p-shell nucleons in ^{12}C . Primary particles emitted from the p-shell are defined in Fig. 5.1.1. The errors are statistical only, the error of the normalization is 15%.

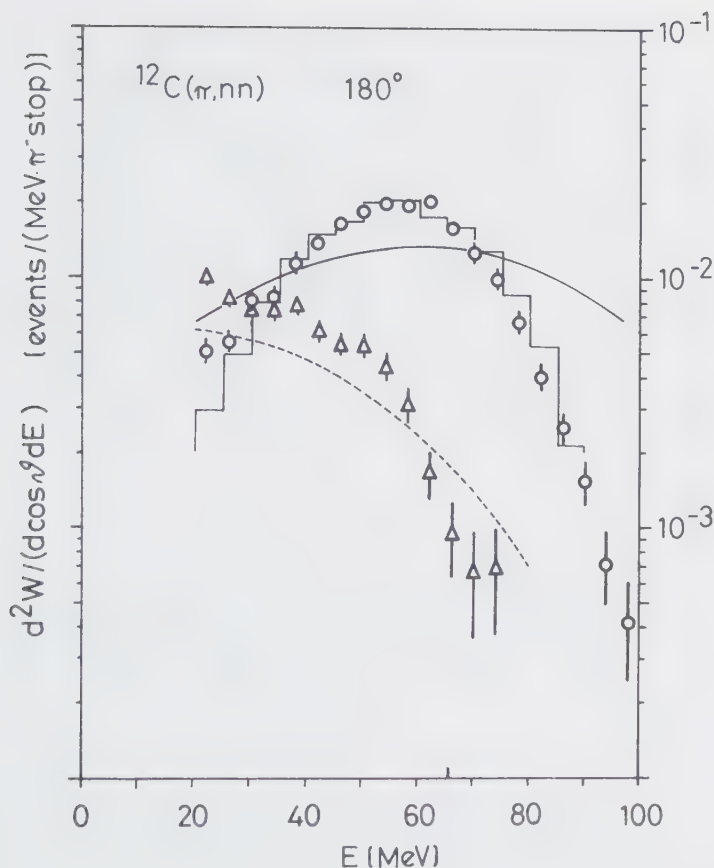


Fig. 5.1.3. Energy spectra of primary (circles) and secondary neutrons (triangles) emitted in $n - n$ coincidences at 180° , after pion absorption in ^{12}C ($E_{n1}, E_{n2} > 20$ MeV, [Isa82]). The errors are statistical only, the error of the normalization is 15%. Primary and secondary neutrons were defined in fig. 5.1.1. The histogram shows the shape of the primary neutron spectrum calculated using a Gaussian matrix element with $\gamma = 160$ MeV/c, normalized to the data. The solid and the dashed lines give the calculated spectra of primary and secondary neutrons obtained by ref. [Chi81].

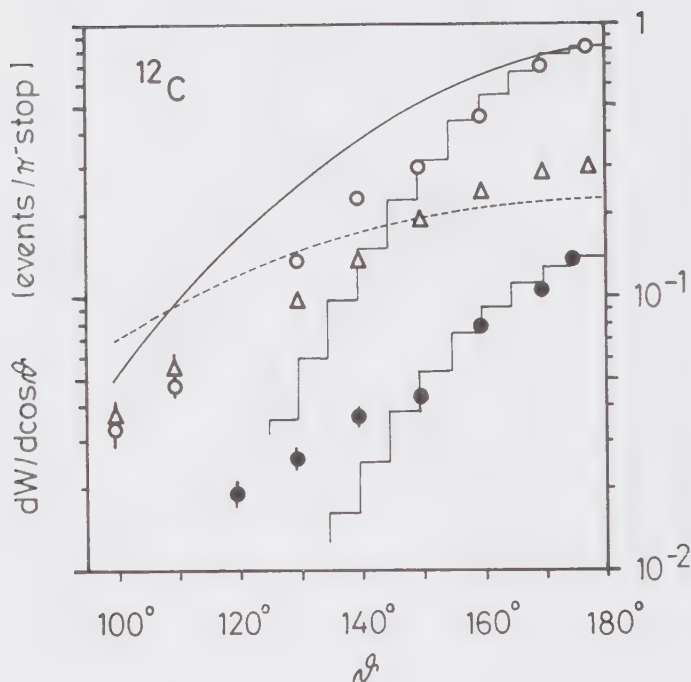


Fig. 5.1.4. Opening angle distribution of primary (open circles, [Isa82]) and secondary n - n pairs (triangles), and opening angle distribution of primary n - p pairs (full circles) emitted after pion absorption in ^{12}C ($E_1, E_2 > 20$ MeV). The errors are statistical only, the error of the normalization is 15%. Primary and secondary n - n and n - p pairs are defined in fig. 5.1.1. The histogram represents the shapes of the opening angle distribution of primary n - n and n - p pairs obtained using a Gaussian matrix element with $\gamma = 160$ MeV/c, ($\beta = 1.60$ fm), normalized to the data. The solid and the dashed lines give the opening angle distributions of primary and secondary n - n pairs, respectively, obtained by ref. [Chi81].

with the residual nucleus. If the residual nucleus is not excited considerably by these processes, these events cannot be identified by the recoil corrected sum energy E_s . Probabilities for the occurrence of large recoil momenta higher than predicted by the simple model may as well explain part of the differences. In the same figure the measured opening angle distribution of primary and secondary $n - n$ pairs are compared with the distributions calculated by ref. [Chi81]. The calculated opening angle distributions are too broad. These discrepancies in the energy spectra and opening angle distributions may be caused by the too large width of the recoil momentum distribution used in the calculation of ref. [Chi81]. It would therefore be interesting to repeat the calculations with a more realistic momentum distribution.

In table 5.1 the yields for the emission of neutron - neutron and neutron - charged particle coincidences are given. They are obtained by integrating the opening angle distributions from 0° to 180° . Lee et al. [Lee72] investigated the coincident emission of neutrons and charged particles ($n - p$, $n - d$, $n - t$). Their yields are also given in table 5.1. and agree with our results. The comparison of their opening angle distributions with our results (fig. 5.1.5.) shows some differences in the shape of the $n - p$ distribution, whereas the $n - d$ and $n - t$ opening angle distributions are in good agreement.

By adding the yields of pairs with energies higher than 20 MeV one obtains $W(\text{coinc}) = 0.50 \pm 0.05 / \pi\text{-stop}$. This means that only 50 % of all absorption processes are followed by the emission of a particle pair with both ejectiles having energies above 20 MeV. The yield of primary nucleon pairs emitted after absorption on quasi-deuterons in the p-shell is $0.19 \pm 0.03 / \pi\text{-stop}$. These

Table 5.1.

Yields of neutron - neutron and neutron - charged particle coincidences with $E_1, E_2 > 20$ MeV for pion absorption in ^{12}C . Yields for the thresholds used by Lee et al. [Lee72] are given for comparison. Yields for quasi-free absorption on quasi-deuterons in the p-shell (see Fig. 5.1.1.) and on α -clusters (fig. 5.2.1.) are also given. c - c is the total yield of charged particle - charged particle coincidences (p, d, t) obtained by ref. [Sen82].

emitted particles	absorption mechanism	Yield ($/\pi$ -stop) ^{12}C	Ref.
n-n	all	0.27(4)	[Isa82] <u>a</u>
n-n	p-shell nucleons	0.15(3)	[Isa82]
n-p	all	0.12(2)	this work
n-p	all	0.06(2)	[Nor68]
n-p	thresholds <u>b</u>	0.076(17)	[Lee72]
n-p	thresholds <u>$\bar{b}$</u>	0.089(15)	this work
n-p	p-shell nucleons	0.035(5)	this work
n-p	p-shell nucleons <u>bc</u>	0.0019(3)	this work
n-p	p-shell nucleons <u>$\bar{bc}$</u>	0.0014(+6, -2)	[Lee72]
n-d	all	0.063(9)	this work
n-d	thresholds <u>b</u>	0.039(9)	[Lee72]
n-d	thresholds <u>$\bar{b}$</u>	0.040(7)	this work
n-t	all	0.019(3)	this work
n-t	thresholds <u>b</u>	0.009(2)	[Lee72]
n-t	thresholds <u>$\bar{b}$</u>	0.009(2)	this work
n-t	α -cluster	0.011(2)	this work
c-c	all	0.020(2)	[Sen82]

a For detailed comparison with other neutron measurements see ref. [Isa82].

b Thresholds are $E_n > 16$ MeV, $E_p > 17$ MeV, $E_d > 24$ MeV and $E_t > 28$ MeV. Integration covered the angles between 110° and 180° .

c Angular range between 170° and 180° .

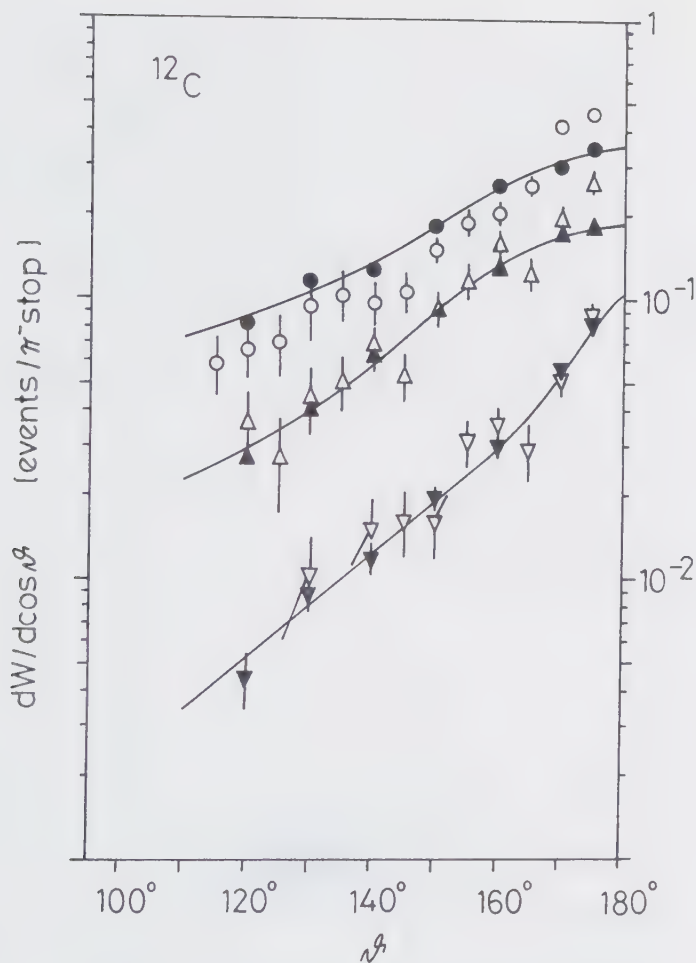


Fig. 5.1.5. Opening angle distributions of $n-p$ (circles), $n-d$ (triangles up) and $n-t$ (triangles down) pairs emitted after pion absorption in ^{12}C . The present data (full symbols) are compared to the data of ref. [Lee72] (open symbols). The errors given for the present work are statistical only, the error of the normalization is 15%. The threshold on the energies of the particles were $E_n > 16$ MeV, $E_p > 17$ MeV, $E_d > 24$ MeV and $E_t > 28$ MeV.

yields are a factor two and three, respectively, lower than the corresponding yields for the lithium isotopes (see table 4.1.), indicating the importance of final state interactions. Chiang and Hüfner [Chi81] obtained in the intranuclear cascade calculation a probability of 33 % that, after pion absorption on quasi-deuterons both nucleons leave the ^{12}C nucleus without final state interaction. Thus the total probability for absorption on quasi-deuterons is $W(qd) = 0.19/0.33 = 0.58 \pm 0.10$ / π -stop. Since not all of the calculated 33 % directly emitted particle pairs have energies above 20 MeV, $W(qd)$ is only a lower limit for the amount of absorption on quasi-deuterons.

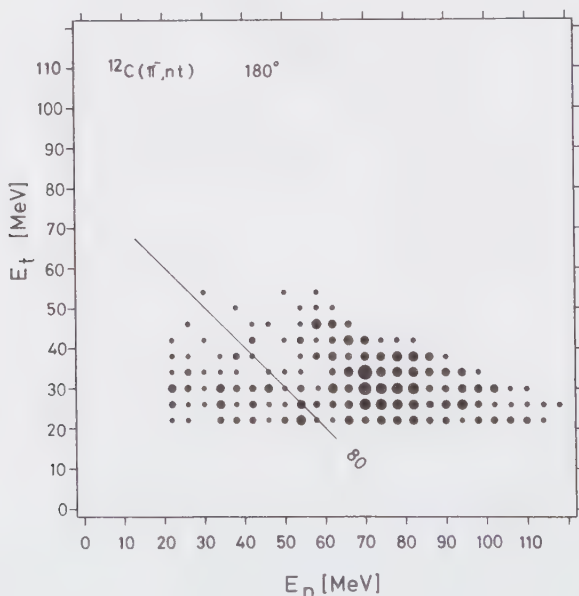


Fig. 5.2.1. Two-dimensional energy spectra $d^3W/dE_n dE_t d\cos\theta$ ($\theta = 180^\circ$) of neutron - triton pairs emitted after pion absorption on an α -cluster in ^{12}C ($E_n, E_t > 20$ MeV). $n - t$ events from quasi-free absorption on an α -cluster are defined by $E_S > 80$ MeV. In appendix B the spectra are also given numerically. (See also fig. 4.1.1.).

5. 2. ABSORPTION ON HEAVIER CLUSTERS IN ^{12}C

Fig. 5.2.1. shows the two-dimensional energy spectrum of neutron - triton pairs emitted after pion absorption in ^{12}C . The maximum around 75 MeV neutron energy and 30 MeV triton energy arises from quasi-free absorption on an α -cluster. The neutron and triton spectra of the primary $n - t$ pairs (see fig. 5.2.2.) are well reproduced by our simple model calculation using the same value for the harmonic oscillator parameter β as for the $n - n$ and $n - p$ spectra. The calculated width of the triton peak is somewhat too large. The opening angle distribution of primary $n - t$ pairs is given in fig. 5.2.3. and compared with the calculation. The width of the calculated distribution is too large. A variation of the harmonic oscillator parameter β from 1.6 fm to 2.0 fm, however, gives a slight improvement for the opening angle distribution and for the triton spectra, whereas the neutron spectrum gets worse. The yield of primary $n - t$ pairs emitted after quasi-free absorption on an α -cluster in ^{12}C is $0.011 \pm 0.002 / \pi$ -stop (table 5.1.). This value gives a lower limit for the amount of absorption on an α -cluster $0.01 / \pi$ -stop. The true value may be much higher because one expects that the final state interactions between the triton and the residual nucleus are very strong and the $n - t$ channel is therefore depleted. An upper limit of $W(\alpha) < 0.46 / \pi$ -stop is given by the estimated amount of absorption on quasi-deuterons.

In a recent paper by Hachenberg [Hac82] the energy spectrum of primary tritons emitted after pion absorption on an α -cluster has been estimated in the following way: the evaporation spectrum and the calculated spectrum of secondary tritons produced by final state interactions after absorption on a quasi-deuteron was subtracted from the measured single triton spectrum of ref. [Pru81]. In Fig. 5.2.4. the primary triton spectrum obtained by this procedure is compared with the measured energy spectrum of tritons emitted in primary $n - t$ pairs after quasi-free absorption of negative pions on an

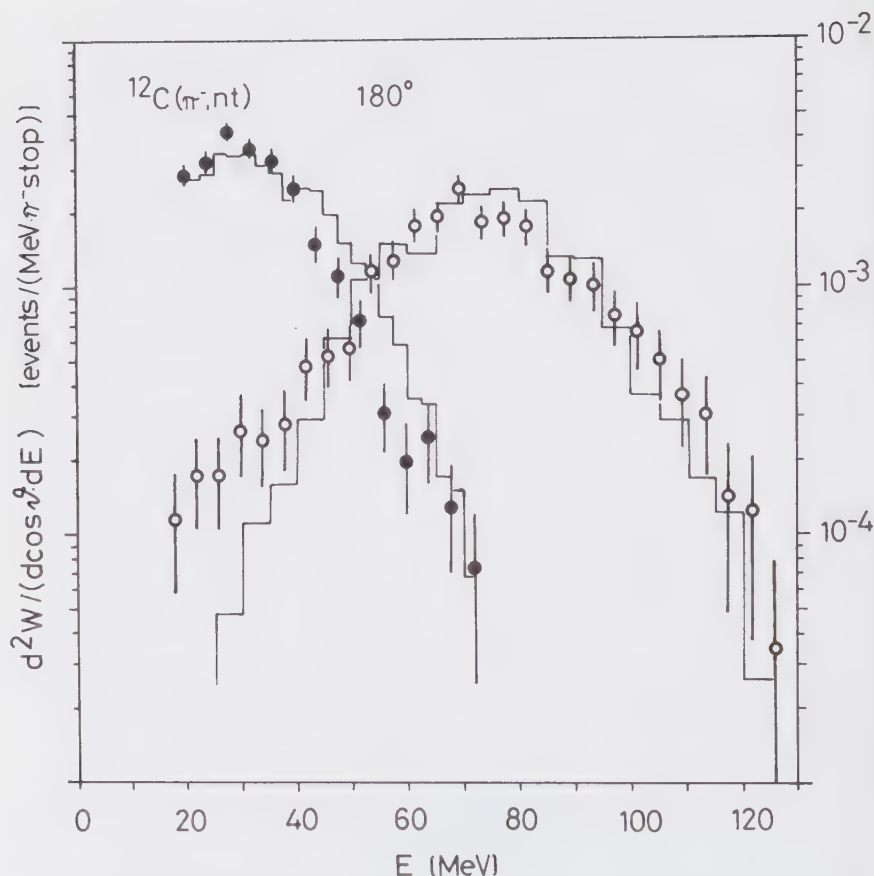


Fig. 5.2.2. Energy spectra of neutrons (open symbols) and tritons (full symbols) emitted in $n - t$ coincidences after quasi-free pion absorption on an α -cluster (see fig. 5.2.1.) in ^{12}C . The errors are statistical only, the error of the normalization is 15%. The histograms show the model calculation using the parameter $\gamma = 202 \text{ MeV/c}$ ($\beta = 1.60 \text{ fm}$). The calculated neutron spectrum is folded with the experimental energy resolution.

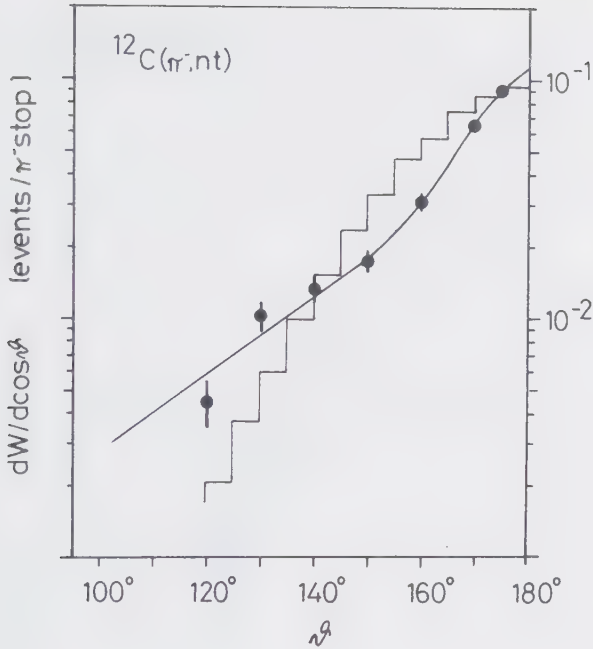


Fig. 5.2.3. Opening angle distribution of $n - t$ pairs ($E_n, E_t > 20$ MeV) emitted after quasi-free pion absorption on an α -cluster in ^{12}C (see fig. 5.2.1.). The errors are statistical only, the error of the normalization is 15%. The solid line represents the fits used for the integration. The histogram shows the distribution obtained by the model calculation using $\gamma = 202$ MeV/c ($\beta = 1.60$ fm)

α -cluster (integrated over the opening angle distribution). Considering the large uncertainties in the procedure of Hachenberg, the agreement between the two spectra is remarkable. In our quasi-free absorption model, the primary triton spectrum can be obtained by an analytical integration of eq. 4 (sect. 2.3.), neglecting the small recoil energy.

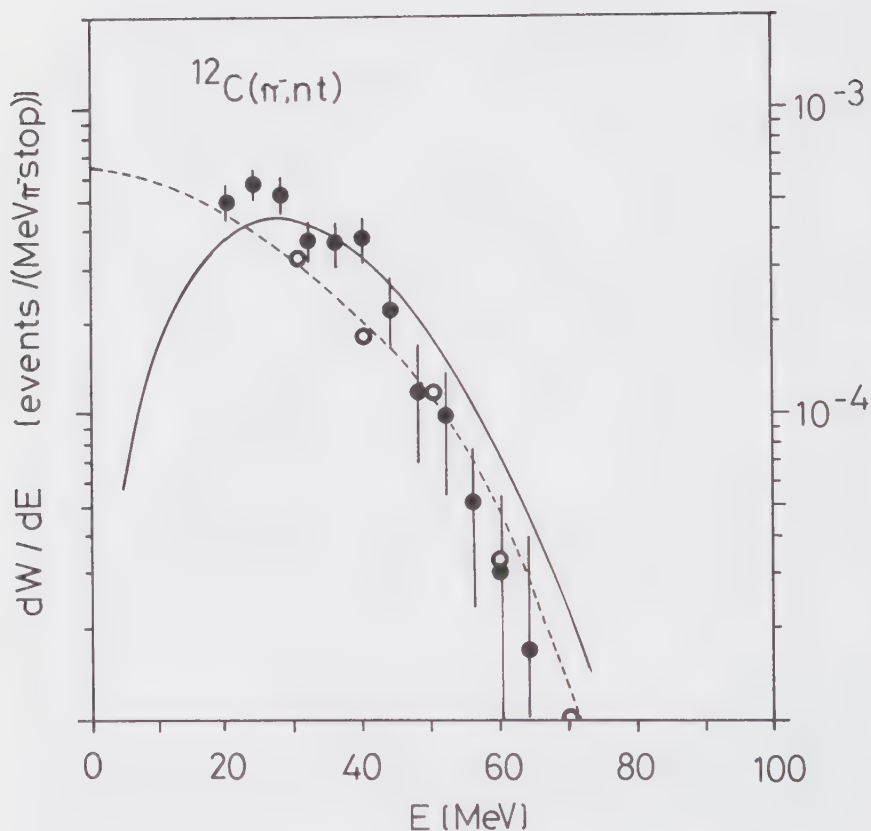


Fig. 5.2.4. Energy spectrum dW/dE ($E_n > 20$ MeV, $0^\circ < \theta < 180^\circ$) of tritons emitted in $n - t$ coincidences after quasi-free pion absorption on an α -cluster in ^{12}C (see fig. 5.2.1., full circles). The solid line is the spectrum obtained by our model calculation using the analytical solution (eq. 6, with $\gamma = 202$ MeV/c, $\beta = 1.6$ fm, normalized to the data). The open circles represent the spectrum of tritons emitted after pion absorption on an α -cluster in ^{12}C , given in ref. [Hac82]. This spectrum was obtained by subtracting the calculated spectrum of secondary tritons emitted after absorption on quasi-deuterons from the measured single triton spectrum of ref. [Pru81]. The dashed line shows the calculated spectrum given by ref. [Hac82] obtained using eq. 7.

Thus,

$$\frac{dW}{dE_t} = e^{-\frac{4}{\gamma^2} E_t} \sinh\left(\frac{4}{\gamma^2} \sqrt{3E_t(Q-E_t)}\right) \quad (6)$$

with $Q(^{12}\text{C}(\pi^-, nt)^8\text{Be}) = 111$ MeV. Hachenberg used the same type of formula for the description of the shape of the primary triton spectrum.

$$\frac{dW}{dE_t} = e^{-\frac{5}{4 E_f} E_t^*} \sinh\left(\frac{5}{4 E_f} \sqrt{3E_t^*(Q-E_t^*)}\right) \quad (7)$$

where E_f is the Fermi energy of ^{12}C (30 MeV) and $E_t^* = E_t + E_{\text{sep}}$. E_{sep} is the separation energy of the triton in the ^{12}C

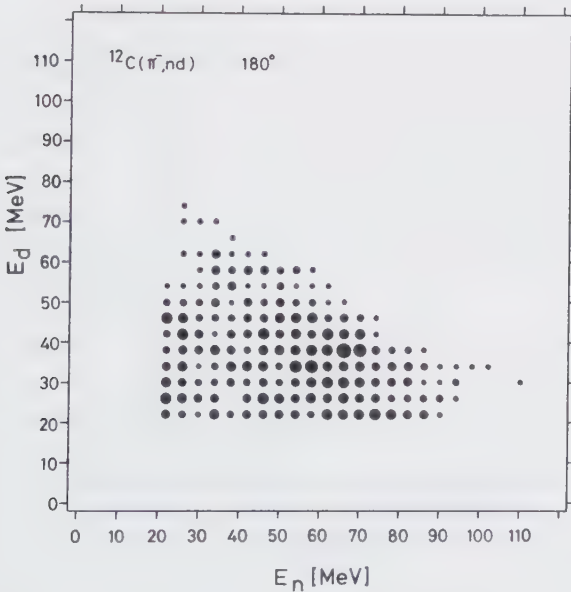


Fig. 5.2.5. Two-dimensional energy spectra $d^3W/dE_n dE_d \cos\theta$ ($\theta = 180^\circ$) of neutron - deuteron pairs, emitted after pion absorption in ^{12}C . ($E_n, E_d > 20$ MeV). In appendix B the spectra are also given numerically. (See also fig. 4.1.1.).

nucleus and is equal to 27.4 MeV. Due to the introduction of the separation energy, this calculation gives a maximum of the triton energy spectrum at 0 MeV. This behaviour is wrong because for small E_f (small γ), corresponding to the limit of absorption on a free α -cluster, the triton spectrum should have a sharp peak at $E_t = Q/4$ (~ 28 MeV). The calculated spectra are given in fig. 5.2.4.

Fig. 5.2.5. shows the two-dimensional energy spectrum of neutron - deuteron pairs emitted after pion absorption in ^{12}C . An enhancement for neutron energies around 70 MeV and deuteron energies around 35 MeV is very broad. Such an enhancement would

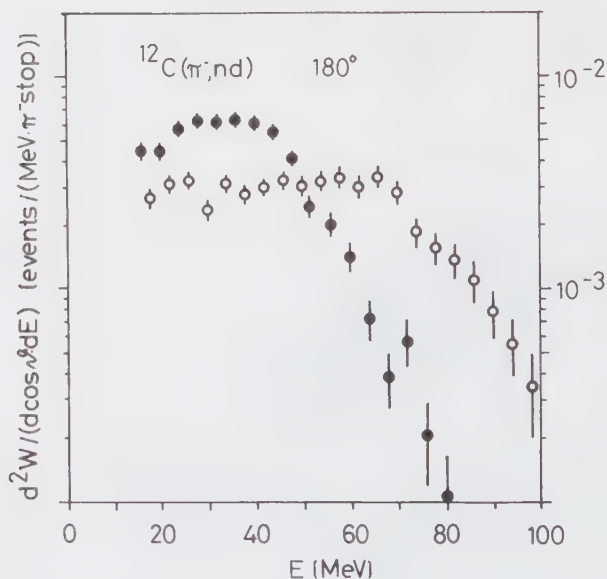


Fig. 5.2.6. Energy spectra of neutrons (open circles, $E_d > 20$ MeV) and deuterons (full circles, $E_n > 20$ MeV) emitted in $n - d$ pairs after pion absorption in ^{12}C . The errors are statistical only, the error of the normalization is 15%.

result from the quasi-free absorption on a ^3He -cluster. It is not possible to separate such primary events from the background of $n - d$ coincidences produced by final state interactions. In fig. 5.2.6. the energy spectra of coincident neutrons and deuterons are shown.

5. 3. PION ABSORPTION IN ^{59}Co AND ^{197}Au

The energy spectra of neutron - neutron and neutron - charged particle pairs emitted after pion absorption in ^{59}Co and ^{197}Au are mainly determined by the final state interaction of the primary nucleons with the residual nucleus. The two-dimensional spectra (given in appendix B) show no clear structure which would allow the separation of primary from secondary pairs. Figs. 5.3.1. and 5.3.2. show the opening angle distributions of neutron - neutron and neutron - charged particle pairs emitted after pion absorption in ^{59}Co and ^{197}Au . The shapes of the distributions are all very similar. The widths (HWHM) are of the order of 50° . The energy spectra for an opening angle of 180° are given in fig. 5.3.3. Within the errors, the spectra of the neutrons and the corresponding charged particles are the same. No significant structures (e.g. an enhancement at 60 MeV in the $n - p$ spectrum) can be observed. By comparing the yields (see table 5.2.) of $n - n$ and $n - p$ pairs ($E_n, E_p > 20$ MeV) lower limits for the value R can be obtained, $R > 1.8$ for ^{59}Co and $R > 2.4$ for ^{197}Au which are smaller than the statistical ratios of 2.5 and 3.0, respectively. Therefore these limits for ^{59}Co and ^{197}Au are not very conclusive, the real value for R may be much higher. Nordberg et al. [Nor68] obtained limits for these ratios of $R > 1.4$ for Cu and $R > 2.0$ for Pb. These limits agree with ours although their measured yields of $n - n$ and $n - p$ pairs are by a factor 2 to 9 lower than ours. From a comparison of the single neutron and proton yields ref. [Pru81] found lower limits of $R > 1.1$ for ^{59}Co and $R > 2.0$ for ^{197}Au . The importance of the final state interaction is also illustrated by the fact that the

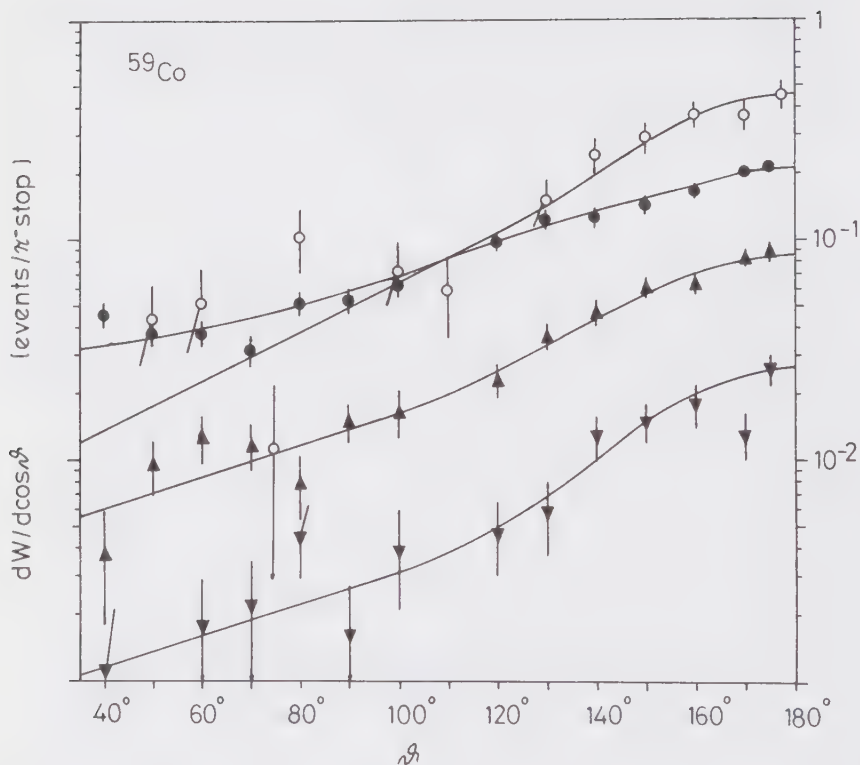


Fig. 5.3.1. Opening angle distribution of $n-n$ (open circles, ref. [Isa82]), $n-p$ (full circles), $n-d$ (triangles up) and $n-t$ pairs (triangles down) emitted after pion absorption in ^{59}Co ($E > 20$ MeV). The errors are statistical only, the error of the normalization is 15%. The solid lines represent the fits used for the integration.

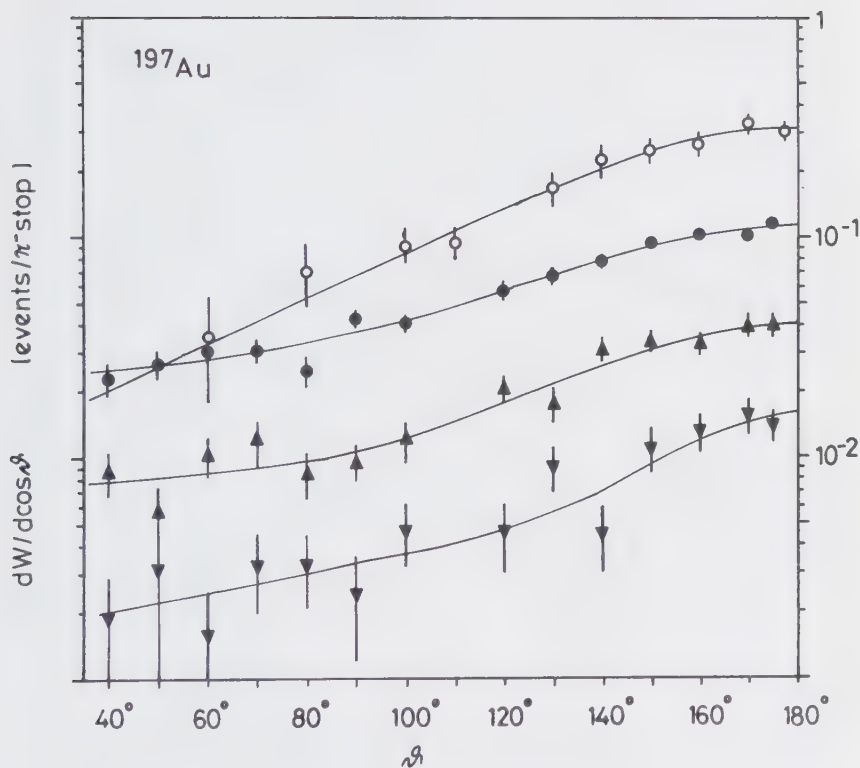


Fig. 5.3.2. Opening angle distribution of $n-n$ (open circles, ref. [Isa82]), $n-p$ (full circles), $n-d$ (triangles up) and $n-t$ pairs (triangles down) emitted after pion absorption in ^{197}Au ($E > 20$ MeV). The errors are statistical only, the error of the normalization is 15%. The solid lines represent the fits used for the integration.

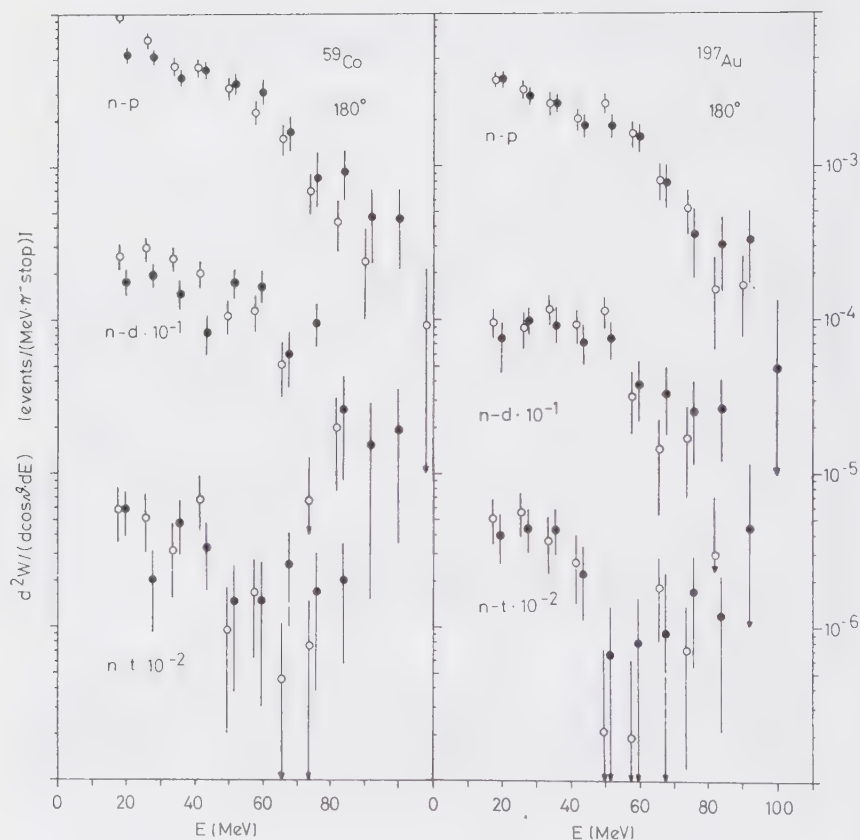


Fig. 5.3.3. Energy spectra of particles emitted in $n-p$, $n-d$ and $n-t$ pairs after pion absorption in ^{59}Co and ^{197}Au . Neutron spectra are given by the full circles, the charged particles by the open ones; the spectrum of the corresponding coincident particle has been integrated above 20 MeV. The errors are statistical only, the error of the normalization is 15%.

probabilities for pair emission ($E > 20$ MeV) are 0.39 ± 0.05 and 0.32 ± 0.05 / π -stop for ^{59}Co and ^{197}Au , compared with 0.50 ± 0.05 / π -stop for ^{12}C and almost 1.0 / π -stop for the lithium isotopes. Thus in a calculation the primary absorption process and final state interactions are necessary to interpret the pion absorption data for the heavy nuclei. Several models were developed recently [Hac80, But80, Chi81, Dat82, Cha82] which calculate the inclusive particle spectra. The agreement with the experimental spectra is good, but the deduced parameters strongly depend on the model. For example the value of R for ^{59}Co varies between 2.5 [Bat80] and 10 [Hac80]. The comparison of these models with the new data on the Ni isotopes [Isa83] and the present coincidence results may help to remove this discrepancy. High values for R , e.g. 18.2 ± 1.1 for ^{177}Yb , were obtained by Orth et al. [Ort82] by selecting experimentally the primary events, defined as events with only two emitted nucleons and the residual nucleus in a bound state.

Table 5.2.

Yields of neutron - neutron and neutron - charged particle coincidences with $E_1, E_2 > 20$ MeV for pion absorption in ^{59}Co and ^{197}Au . c - c is the total yield of charged particle - charged particle coincidences (p, d, t) obtained by ref. [Sen82].

emitted particles	Yield ($/\pi$ -stop)		Ref.
	^{59}Co	^{197}Au	
n-n	0.19(4)	0.19(4)	[Isa82]
n-p	0.14(3)	0.09(2)	this work
n-d	0.04(1)	0.029(7)	this work
n-t	0.009(3)	0.008(3)	this work
c-c	0.013(2)	0.006(1)	[Sen82]

6. SUMMARY AND CONCLUSIONS

Energy spectra $d^3W/dE_1dE_2d\cos\theta$ of neutron - charged particle pairs emitted after the absorption of stopped negative pions in ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{12}\text{C}$, ${}^{59}\text{Co}$ and ${}^{197}\text{Au}$ have been measured for opening angles between 50° and 180° . For the lithium isotopes and for carbon, pairs emitted after quasi-free absorption on a quasi-deuteron or on a heavier cluster (primary events) could be separated from those where at least one of the nucleons lost energy in final state interaction with the residual nucleus. This separation allowed the study of the primary absorption process without requiring a model for final state interactions. The spectra are discussed together with the data of [Har78, Isa82] on the emission of neutron - neutron pairs after pion absorption in the same target nuclei.

The quasi-deuteron mechanism was found to be the dominant reaction. For this channel the ratio R of np to pp pairs that absorb the pion was determined for pion absorption in the p -shell of ${}^{12}\text{C}$. The value $R(p\text{-shell}) = 6.3 \pm 1.4$ is larger by a factor of two than the statistical ratio $R_{st} = 2N_p/(Z_p-1) = 2.7$. (N_p and Z_p are the numbers of neutrons and protons in the p -shell of the nucleus). For the lithium isotopes the ratio $R(p\text{-shell})$ is infinite (no pp pairs in the p -shell), whereas for pion absorption involving s -shell nucleons lower limits of $R(s\text{-shell}) > 4.4$ for ${}^6\text{Li}$ and $R(s\text{-shell}) > 7.8$ for ${}^7\text{Li}$ were deduced. Both values are considerably higher than the statistical values. The lower limits of $R > 1.8$ given for ${}^{59}\text{Co}$ and $R > 2.5$ for ${}^{197}\text{Au}$ are smaller than the corresponding statistical values and are therefore less conclusive.

Lower limits for the probability for pion absorption on heavier clusters (${}^3\text{He}$ or α -cluster) are $W(hc) > 0.16$ for ${}^6\text{Li}$ and $W(hc) > 0.11$ for ${}^7\text{Li}$. These limits were found from the investigation of quasi-free emission of $n-d$ and $n-t$ pairs. The probability for pion absorption on an α -cluster in ${}^{12}\text{C}$ was estimated to be

$W(\alpha) > 0.01$. It was obtained from the yield of primary $n - t$ pairs. A small fraction of the pions is also absorbed on ${}^4\text{Li}$ -clusters or even on heavier clusters [Sen82].

The total yield of neutron - neutron, neutron - charged particle and charged particle - charged particle pairs emitted, with both particles having energies larger than 20 MeV, is

0.91 ± 0.11 / π -stop for ${}^6\text{Li}$,
 0.94 ± 0.11 / π -stop for ${}^7\text{Li}$,
 0.50 ± 0.05 / π -stop for ${}^{12}\text{C}$,
 0.39 ± 0.05 / π -stop for ${}^{59}\text{Co}$
 and 0.32 ± 0.05 / π -stop for ${}^{197}\text{Au}$.

The total yield of primary particle pairs is

0.70 ± 0.07 / π -stop for ${}^6\text{Li}$,
 0.71 ± 0.07 / π -stop for ${}^7\text{Li}$
 and 0.20 ± 0.04 / π -stop for ${}^{12}\text{C}$.

For the heavier nuclei ${}^{59}\text{Co}$ and ${}^{197}\text{Au}$ no primary events could be identified, and thus only an upper limit of 0.15 / π -stop for the probability of the emission of primary pairs can be given. These numbers exhibit the great importance of final state interactions for pion absorption in the heavier nuclei ${}^{12}\text{C}$, ${}^{59}\text{Co}$ and ${}^{197}\text{Au}$, while for the lithium isotopes final state interactions are of minor importance and 2/3 of all particle pairs leave the nucleus without final state interactions.

For ${}^{12}\text{C}$ model calculations including final state interactions exist [Chi81,Hac82]. The experimental $n - n$ opening angle distributions and energy spectra for both, primary and secondary pairs are reasonably well explained by these calculations. Hachenberg [Hac82] also compared his calculated spectrum with the experimental inclusive triton spectrum [Pru81] and deduced that high energy tritons are mainly produced by final state interactions of the primary nucleon pair, and a small contribution stems from quasi-free absorption on an α -cluster. This deduced primary component of the inclusive triton energy spectrum is in agreement with the measured triton energy

spectrum of primary n-t pairs.

For the quasi-free absorption the shapes of the energy spectra and opening angle distributions depend mainly on the momentum distribution of the absorbing pair or heavier cluster, relative to the residual nucleus (recoil momentum distribution). From other nuclear reactions it is known that in first order the momentum distribution can be described by a Gaussian function $\sim \exp(-P^2/\gamma^2)$. The parameters γ were taken from (p,pd) [Alb80], (p,pa) [Jai70], (e,e) [Jae74] and (γ ,pn) reactions [Kho81] investigating the momentum distributions of quasi-deuteron in the nuclei ${}^6\text{Li}$, ${}^7\text{Li}$ and ${}^{12}\text{C}$. The smallness of the parameter $\gamma = 50 \text{ MeV/c}$ for ${}^6\text{Li}$, compared to 100 MeV/c for ${}^7\text{Li}$ shows that the relative momenta between the α and d clusters in ${}^6\text{Li}$ are much smaller than between the α and t clusters in ${}^7\text{Li}$. For ${}^{12}\text{C}$ $\gamma = 160 \text{ MeV/c}$ was used. The agreement between calculated and experimental shapes of the energy spectra and opening angle distributions is good at large opening angles. The deviations at smaller opening angles may be explained by nucleon - nucleus final state interactions or by a momentum distribution with an enhancement in the tail at high recoil momenta, compared to the model. To understand these deviations and to calculate the yields of the different absorption channels (n - n, n - p, n - d, n - t) a more sophisticated model using a microscopic absorption operator and nucleon wave functions is necessary.

ACKNOWLEDGEMENTS

I would like to thank my advisor Prof. Dr. R. Engfer for giving me the possibility to work in his group, for the freedom I had and for his continuous interest in the work.

I am very grateful to H.S. Pruis for the innumerable hours of discussion devoted to me, for his valuable suggestions and for his helpful criticism. He initialized the measurements and took main responsibilities for the experiments; his guidance was a great help for me.

H.P. Isaak, U. Sennhauser and T. Kozlowski are acknowledged for the agreeable collaboration during the experiment and the evaluation. I am indebted to E.A. Hermes for the construction of the experimental setup.

I thank also all other members of the University - ETH Zürich collaboration for their assistance during the runs and for the atmosphere in the group. This includes W. Bertl, L. Felawka, C. Grab, J. v.d.Pluym, R. Powers, A. v.d.Schaaf, F. Schlepütz, R. Winter, H.K. Walter and A. Zglinski.

I am grateful to Prof. Dr. C.U. Mayer-Böricke and Drs. G. Riepe, A. Hamacher and D. Protic of KfA Jülich for the production and the repair of the Ge detectors. Without their help, the completion of the experiment would have been impossible.

The Physics Institute of the University Zürich, the Swiss National Science Foundation and the Swiss Institut for Nuclear Research (SIN) are acknowledged for their support.

Last, but not least, I thank my wife and my children for their indulgence and patience during the time I was working on this project.

APPENDIX A: SIMPLE MATRIX ELEMENT FOR PION ABSORPTION

For quasi-free absorption the matrix element contains only the wave function of the quasi-deuteron $\psi_d(\vec{R}, \vec{r})$ and the wavefunction of the two emitted nucleons, $\psi_{NN}(\vec{R}, \vec{r})$. $\vec{R}$ is the coordinate of the centre of mass of the quasi-deuteron, $\vec{r}$ is the relative coordinate of the nucleon in the quasi-deuteron; $\vec{P}$ and $\vec{p}$ are the momenta of the quasi-deuteron and the relative momentum of the nucleons in the quasi-deuteron, respectively. Thus

$$M = \int \psi_{NN}^*(\vec{R}, \vec{r}) V_{\pi NN} \psi_d(\vec{R}, \vec{r}) d^3\vec{R} d^3\vec{r}$$

Since the interaction $V_{\pi NN}$ is of short range, it can be approximated by a point interaction [Chi81]

$$V_{\pi NN}(\vec{R}, \vec{r}) = \text{const} \cdot \delta(\vec{r})$$

In the independent particle model with harmonic oscillator wave functions the quasi-deuteron wave function $\psi_d(\vec{R}, \vec{r})$ is given by

$$\psi_d(\vec{R}, \vec{r}) \sim e^{-\frac{R^2}{\beta^2} - \frac{r^2}{4\beta^2}}$$

with $\beta = \sqrt{\hbar/m\omega}$ the harmonic oscillator strength parameter. The emitted nucleons are free particles. Thus

$$\psi_{NN}(\vec{R}, \vec{r}) \sim e^{-\frac{i(\vec{P}\vec{R} + \vec{p}\vec{r})}{\hbar}}$$

Using the δ -function of the interaction the integration over the relative coordinates gives

$$M \sim \int e^{\frac{i}{\hbar} \vec{P} \vec{R}} e^{-\frac{R^2}{\beta^2}} d^3 \vec{R}$$

The remaining integral is a simple Fourier transformation

$$M \sim e^{-\frac{1}{4} \left(\frac{\beta P}{\hbar} \right)^2}$$

For light nuclei a factor $A/(A-2)$ resulting from the reduced mass between $2m_N$ and m_{A-2} has to be taken into account [Sak66].

$$M \sim e^{-\frac{1}{4} \frac{A}{A-2} \left(\frac{\beta P}{\hbar} \right)^2} = e^{-\frac{1}{2} \left(\frac{P}{\gamma} \right)^2}$$

$$\gamma = \sqrt{\frac{2(A-2)}{A}} \frac{\hbar}{\beta}$$

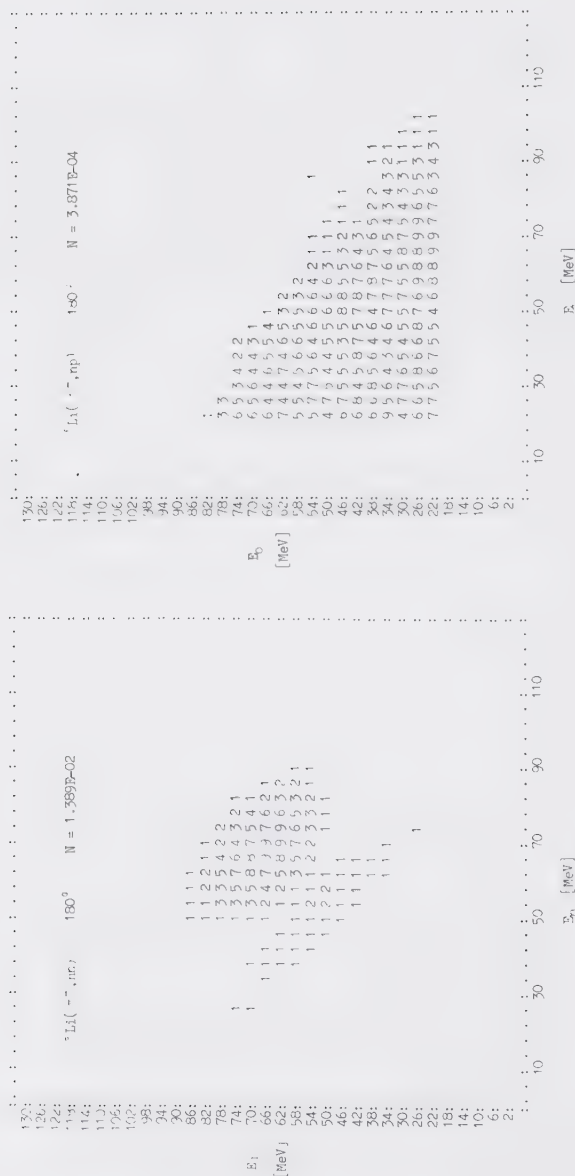
The extension to pion absorption on heavier clusters with n nucleons is straight forward:

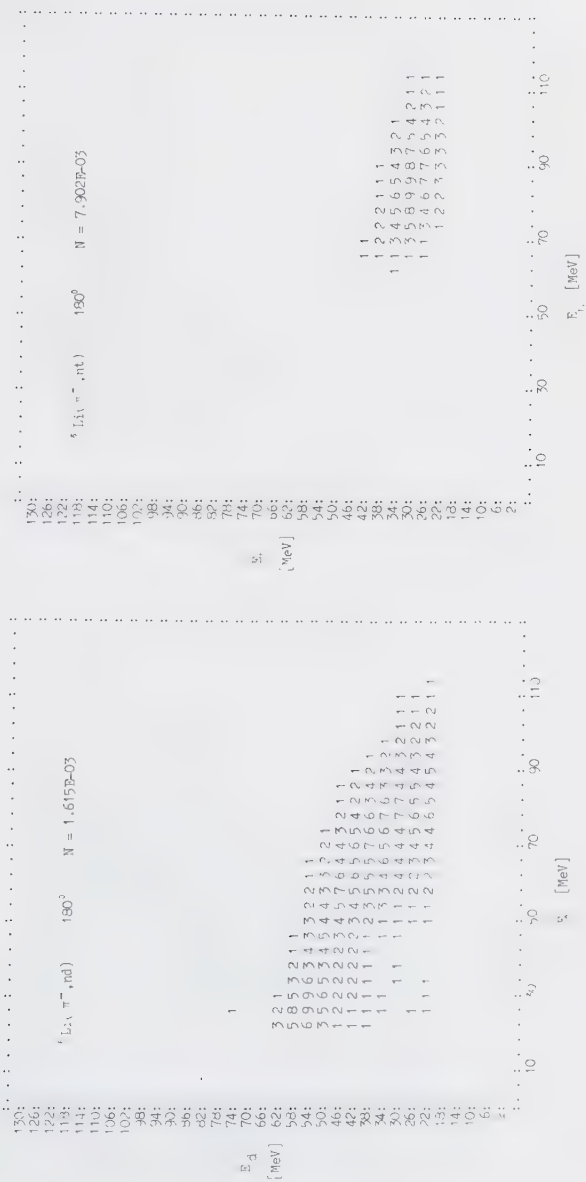
$$M \sim e^{-\frac{1}{2} \left(\frac{P}{\gamma} \right)^2}$$

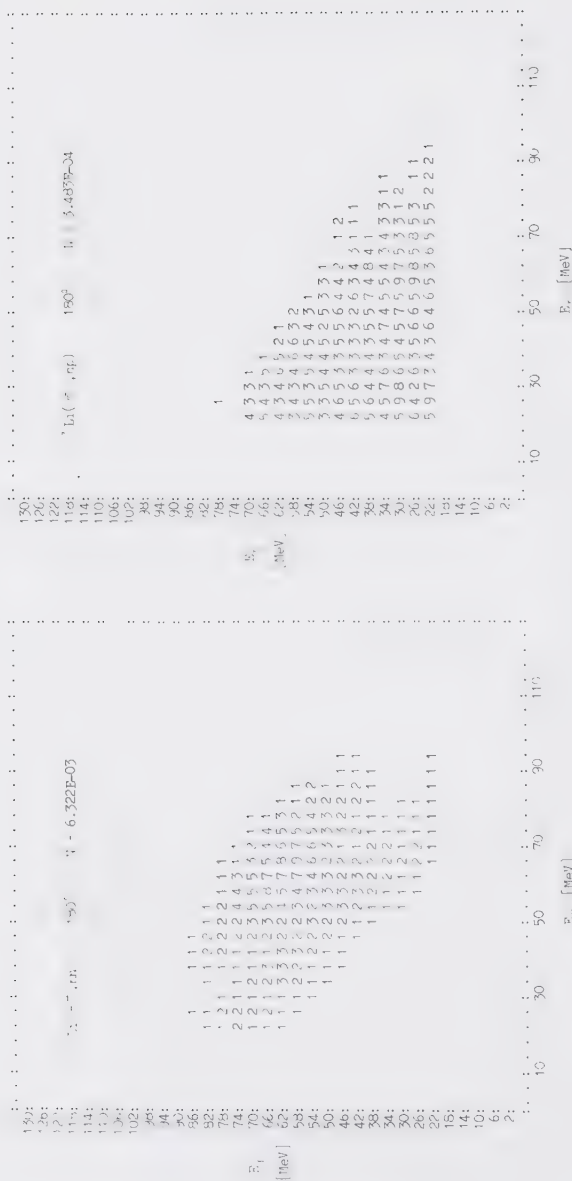
$$\gamma = \sqrt{\frac{n(A-n)}{A}} \frac{\hbar}{\beta}$$

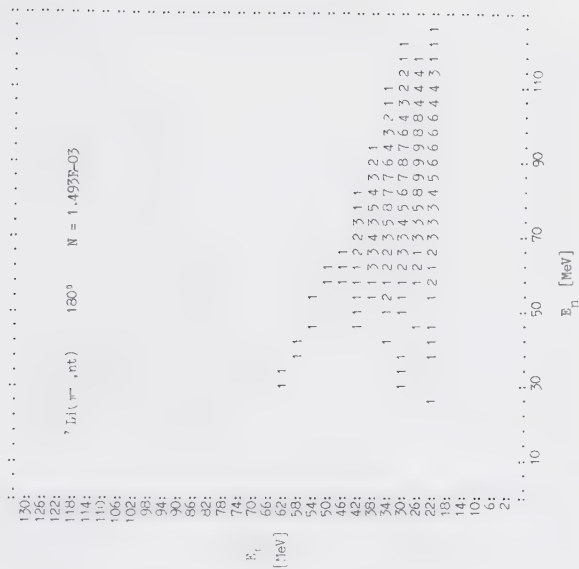
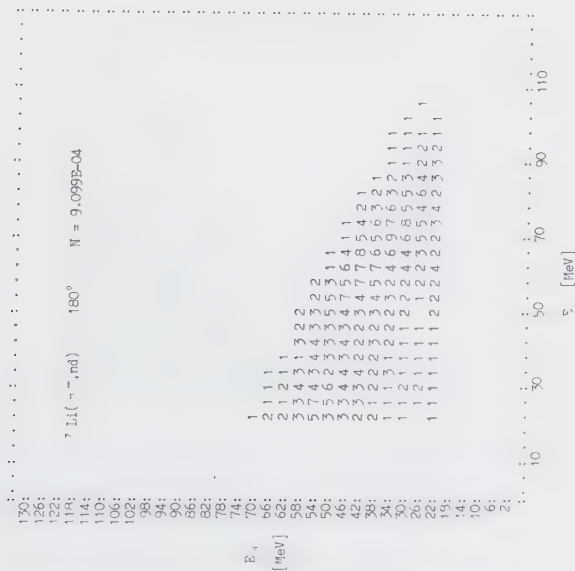
APPENDIX B: TWO-DIMENSIONAL ENERGY SPECTRA

Two-dimensional energy spectra $d^3W/dE_1dE_2d\cos\theta$ ($\theta = 180^\circ$) of $n - n$, $n - p$, $n - d$ and $n - t$ pairs emitted after pion absorption in ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{12}\text{C}$, ${}^{59}\text{Co}$ and ${}^{197}\text{Au}$ ($E_1, E_2 > 20$ MeV). N is the intensity of the maximum of the two-dimensional distribution [events/(MeV² π -stop)]. The intensities are given by the numbers; 9 stands for intensities between 0.9 N and 1.0 N , 8 for intensities between 0.8 N and 0.899 N etc. The intensities below 0.1 N are not given. The $n - n$ data are from ref. [Isa82].

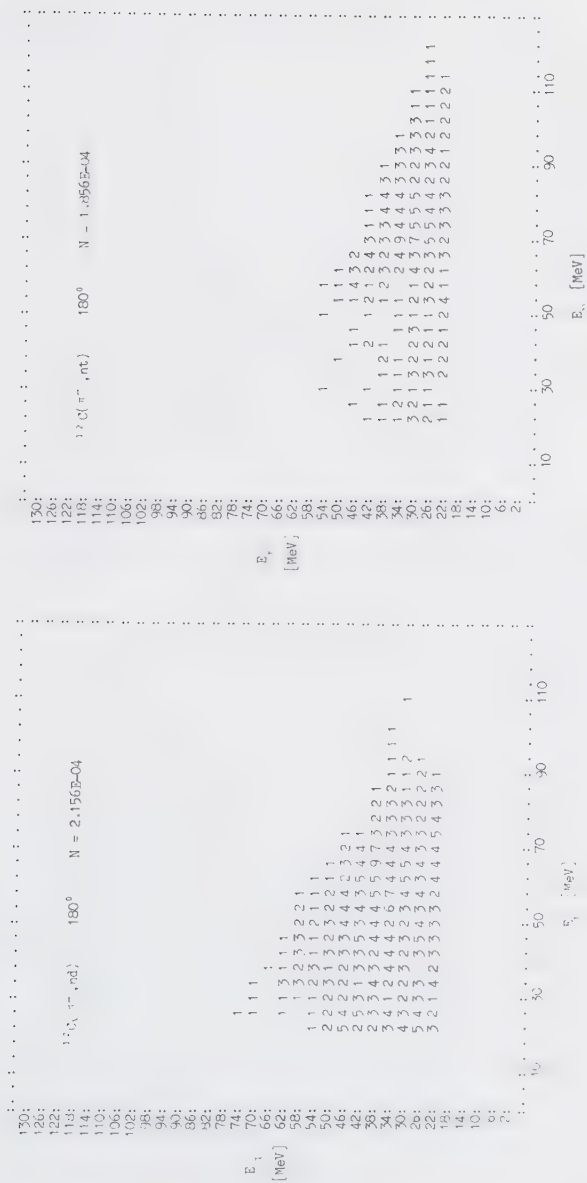


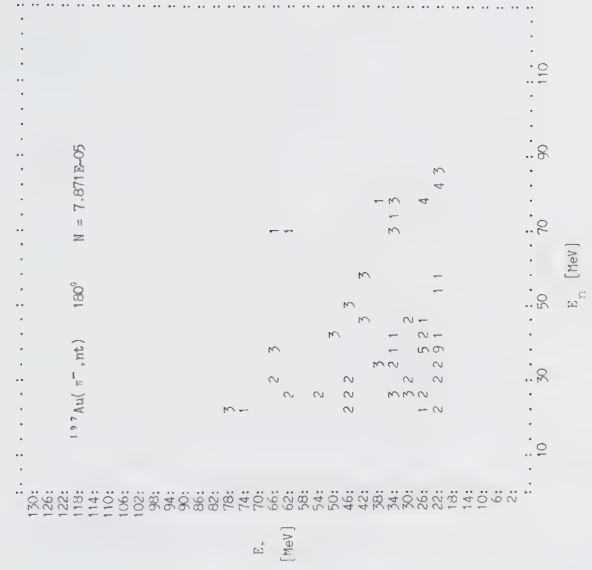
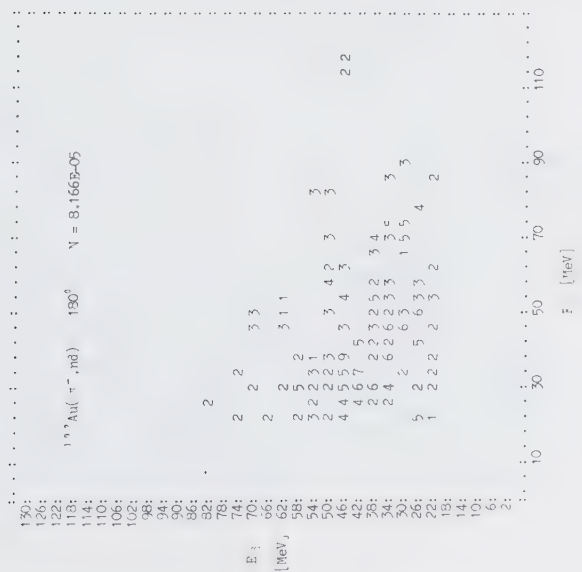












REFERENCES

- [Alb80] D.Albrecht, M.Csatlos, J.Erő, Z.Fodor, I.Hernyes, Hongsung Mu, B.A.Khomenko, N.N.Khovanskiĭ, P.Koncz, Z.V.Krumstein, Yu.P.Merekov, V.I.Petrukhin, Z.Seres and L.Vegh, Nucl. Phys. A338 (1980) 477
- [Ang79] M.Anghinolfi, G.Ricco, P.Corvisiero and F.Masulli, Nucl. Instr. and Meth. 165 (1979) 217
- [Bar73] R.J.Barrett, J.McCarthy, R.C.Minehart and K.Ziock, Nucl. Phys. A216 (1973) 145
- [Ber78] G.F.Bertsch and D.O.Riska, Phys. Rev. C18 (1978) 317
- [Blo63] M.M.Block, T.Kikuchi, D.Koetke, J.Kopelman, C.R.Sun, R.Walker, G.Culligan, V.L.Teleghi and R.Winston, Phys. Rev. Lett. 11 (1963) 301
- [But80] V.S.Buttsev, A.S.Iljinov and S.E.Chigrinov, Sov. J. Part. and Nucl. 11 (1980) 358
- [Cal70] P.Calligaris, C.Cernigoi, I.Gabrielli and F.Pellegrini, 3rd International Conference on High Energy Physics and Nuclear Structure, New York (1970) 367
- [Cer81] C.Cernigoi, I.Gabrielli, N.Grion, G.Pauli, B.Saitta, R.A.Ricci, P.Boccaccio and G.Viesti, Nucl. Phys. A352 (1981) 343
- [Cha82] A.Chatterjee and S.K.Gupta, Z. Phys. A307 (1982) 269
- [Che69] D.L.Cheshire and S.E.Sobottka, Phys. Lett. 30B (1969) 244 Nucl. Phys. A146 (1970) 129
- [Chi81] H.C.Chiang and J.Hüfner, Nucl. Phys. A352 (1981) 442
- [Dat82] V.M.Datar and B.K.Jain, Phys. Rev. C26 (1982) 616
- [Dro72] M.Drosg, Nucl. Instr. and Meth. 105 (1972) 573
- [Fow80] J.L.Fowler, J.A.Cookson, M.Hussain, R.B.Schwartz, M.T.Swinhoe, C.Wise and C.A.Uttley, Nucl. Instr. and Meth. 175 (1980) 449
- [Gad76] E.Gadioli and E.Gadioli-Erba, Nucl. Phys. A256 (1976) 414; Contribution G33, 9-ICOHEPANS, Versailles (1981)
- [Gue76] A.Del Guerra, Nucl. Instr. and Meth. 135 (1976) 337
- [Hac80] P.Hachenberg, H.C.Chiang and J.Hüfner, Phys. Lett. 97B (1980) 183
- [Hac82] P.Hachenberg, Phys. Lett. 113B (1982) 451
- [Har78] R.Hartmann, H.P.Isaak, R.Engfer, E.A.Hermes, H.S.Pruys, W.Dey, H.J.Pfeiffer, U.Sennhauser, H.K.Walter and J.Morgenstern, Nucl. Phys. A308 (1978) 345
- [Heu82] P.Heusi, H.P.Isaak, H.S.Pruys, R.Engfer, U.Sennhauser and H.K.Walter, SIN preprint PR 82-11 (1982) and Contribution to the 3rd International Conference on Nuclear Reaction Mechanisms, Varenna (1982)
- [Ilj76] A.S.Iljinov and V.I.Nazaruk, Nucl. Phys. A268 (1976) 513
- [Isa82] H.P.Isaak, P.Heusi, H.S.Pruys, R.Engfer, E.A.Hermes, T.Kozlowski, U.Sennhauser and H.K.Walter, SIN Preprint PR-82-15 (1982), submitted to Helv. Phys. Acta

- [Isa83] H.P.Isaak, H.S.Pruys, R.Engfer, R.Hartmann, E.A.Hermes, F.W.Schleppütz, A.Zgliniski, T.Kozlowski, U.Sennhauser and H.K.Walter, Nucl. Phys. A 392 (1983) 385
- [Jae74] C.W.Jaeger, H.de Vries and C.de Vries, At. Data Nucl. Data tables 14 (1974) 479
- [Jai70] M.Jain, P.G.Roos, H.G.Pugh and H.D.Holmgren, Nucl. Phys. A153 (1970) 49
- [Jam70] F.James, CERN Program Library W505, (1970)
- [Käl82] G.Kälbermann and J.M.Eisenberg, Nucl. Phys. A382 (1982) 413
- [Kho81] A.F.Khodyachikh, P.I.Vatset, V.N.Gur'ev, I.V.Dogyust and V.V.Kirichenko, Sov. J. Nucl. Phys. 34 (1981) 789, Sov. J. Nucl. Phys. 32 (1980) 453
- [Kit75] P.Kitching, W.C.Olsen, H.S.Sherif, W.Dollhopf, C.Lunke, C.F.Perdrisat, J.R.Priest and W.K.Roberts, Phys. Rev. C11 (1975) 420
- [Kol67] D.S.Koltun and A.Reitan, Phys. Rev. 155 (1967) 1139
- [Lee72] D.M.Lee, R.C.Minehart, S.E.Sobottka and K.O.H.Ziock, Nucl. Phys. A182 (1972) 20; Nucl. Phys. A197 (1972) 106
- [Muk79] N.C.Mukhopadhyay, J.Hadernann and K.Junker, Nucl. Phys. A319 (1979) 448
- [Nau74] M.W.McNaughton, F.Brady, W.B.Broste, A.L.Sagle and S.W.Johnson, Nucl. Instr. and Meth. 116 (1974) 25
- [Nor68] M.E.Nordberg, Jr., K.F.Kinsey and R.L.Burman, Phys. Rev. 165 (1968) 1096
- [Nym73] E.M.Nyman, Nucl. Phys. A215 (1973) 397
- [Ort82] C.J.Orth, B.J.Dropesky, G.C.Giesler, L.-C.Liu, R.S.Rundberg and V.L.Rundberg, Phys. Rev. C26 (1982) 1571
- [Oza60] S.Ozaki, R.Weinstein, G.Glass, E.Loh, L.Neimala, A.Wattenberg, Phys. Rev. Lett. 4 (1960) 533
- [Pru79] H.S.Pruys, R.Engfer, R.Hartmann, U.Sennhauser, H.J.Pfeiffer, H.K.Walter, J.Morgenstern, A.Wyittenbach, E.Gadioli and E.Gadioli-Erba, Nucl. Phys. A316 (1979) 365
- [Pru81] H.S.Pruys, R.Engfer, R.Hartmann, E.A.Hermes, H.P.Isaak, F.W.Schleppütz, U.Sennhauser, W.Dey, K.Hess, H.J.Pfeiffer, H.K.Walter and W.Hesselink, Nucl. Phys. A352 (1981) 388
- [Rid74] R.A.J.Riddle, G.H.Harrison, P.G.Roos and M.J.Saltmarsh, Nucl. Instr. and Meth. 121 (1974) 445

- [Sak66] Y.Sakamoto, Nucl. Phys. 87 (1966) 414
[Sak75] Y.Sakamoto, P.Cuer and F.Takeutchi, Phys. Rev. C11
(1975) 668
[Sen81] U.Sennhauser, L.Felawka, T.Kozlowski, H.K.Walter,
F.W.Schlepütz, R.Engfer, E.A.Hermes, P.Heusi,
H.P.Isaak, H.S.Pruys, A.Zglinski and W.H.A.Hesselink,
Phys. Lett. 103B (1981) 409
[Sen82] U.Sennhauser, H.J.Pfeiffer, H.K.Walter, F.W.Schlepütz,
H.S.Pruys, R.Engfer, R.Hartmann, E.A.Hermes, P.Heusi,
H.P.Isaak, and W.H.A.Hesselink, Nucl. Phys. A386 (1982)
429
U.Sennhauser, W.Dey, H.J.Pfeiffer, H.K.Walter,
H.S.Pruys, F.W.Schlepütz, R.Engfer, R.Hartmann,
E.A.Hermes, P.Heusi, H.P.Isaak, and W.H.A.Hesselink,
Nucl. Phys. A386 (1982) 447
[Shi80] K.Shimizu and A.Faessler, Nucl. Phys. A333 (1980) 495
[Ver78] P.Vernin, SACLAY, private communication (1978)
[Zio70] K.O.H.Ziock, C.Cernigoi, G.Gorini, Phys. Lett. 33B
(1970) 471

CURRICULUM VITAE

Name	Heusi Peter Adolf
Heimatort	Schleitheim SH
Geburtsdatum	9. Mai 1953
Geburtsort	Erlenbach ZH
1966 - 1972	Kantonsschule Zürcher-Oberland, Wetzikon
1972	Maturität B
1972 - 1979	Studium der Physik an der Universität Zürich
1979	Diplom als Experimentalphysiker
seit 1979	Assistent und Doktorand am Physik-Institut der Universität Zürich

Die Dissertation entstand unter der Leitung von Herrn Prof.
Dr. R. Engfer.

Verzeichnis der Dozenten deren Vorlesungen ich besuchte:

J. Benn, D. Brinkmann, E. Brun, R. Engfer, W. Heinzelmann,
H.H. Keller, G. Karrer, W. Kündig, H. Labhart,
M. P. Locher, V. Meyer, H.H. Müller, U. Niederer,
R.E. Pixley, G. Rasche, W. Reichart, G. Scharf,
H.R. Schwarz, A. Steiner, N. Straumann, K. Strebel,
H. Stüssi, A. Thellung, P. Truöl, F. Waldner.

